SPATIAL AND TEMPORAL DYNAMICS OF FINE FLUVIAL SEDIMENT TRANSFER: IMPLICATIONS FOR MONITORING AND MANAGEMENT OF UPLAND RIVER SYSTEMS

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SPATIAL AND TEMPORAL DYNAMICS OF FINE FLUVIAL SEDIMENT TRANSFER: IMPLICATIONS FOR MONITORING AND MANAGEMENT OF UPLAND RIVER SYSTEMS

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Spatial and temporal dynamics of fine fluvial sediment transfer: implications for monitoring and management of upland river systems

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Although the impacts of changing land use on the magnitude and timing of erosion in lowland catchments are well documented, much less is known about the transfer dynamics of fine sediment through the upland hydrological networks. Using a novel distributed monitoring approach, this thesis examines the magnitude, timing and physical characteristics of fluvial fine sediment in two adjacent upland rivers in North Yorkshire (UK). Annual suspended sediment yield (SSY) estimates range from 33.92 t km^{-2} in the 131 km^{2} Upper Derwent catchment to 57.91 t km^{-2} in the 96 km^{2} River Esk catchment. Infrequent events were found to be of greatest importance, transferring up to 38% of the annual load in under two days. Simple annual and seasonal rating curves were constructed and are effective in predicting SSC with relative errors of less than 15%. Analysis of within-storm fine sediment dynamics indicated the dominance of sources proximal to the channel in the Esk catchment, whereas sediment sources in the Upper Derwent were more variable. Distributed time-integrated fine sediment sampling identified high SSYs in the headwaters of the Upper Derwent whereas in the headwaters of the Esk the minimum SSY was found with tributaries draining the central valley having maximum SSYs. Analysis of the absolute particle size observed significant downstream fining in both catchments and strong positive relationships between flow and particle size of the transported sediment. The data collected are also applied to four real-world scenarios to demonstrate the effectiveness of this approach. This research has enhanced our understanding of fine sediment delivery to upland channels through the assessment of the fine sediment dynamics at a range of temporal and spatial scales rarely studied in these environments.

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Declaration

This thesis, or material contained within it, has not been previously submitted for a degree in this or any other university. Where relevant, all material which is the work of others has been acknowledged.

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Chapter 1: Research Context

1.1 Rationale

Although there is a considerable knowledge base of the impacts of changing land use on the magnitude and timing of terrestrial erosion within modified catchments, much less is known about the transfer dynamics of fine sediment through the upland hydrological networks. The impact of fine sediment delivery to drainage networks is of considerable concern given that physical issues associated with the transfer of this mobilised fine sediment into river networks include the reduced lifespan of dams and reservoirs (Shalash, 1982), impairment of navigation on waterways (Gottschalk, 1945), increases in the potential for flooding due to severe aggradation of river bed, and damage to roads and houses following muddy flows. The ecological impacts of fine sediment in watercourses are also well documented (cf. Wood and Armitage, 1997). Some of the most harmful effects include: limits to the primary productivity in the river as a result of increases in turbidity, reducing the natural penetration of light (Nieuwenhuyse and LaPerriere, 1986), increases in the drift of benthic organisms (Rosenberg and Wiens, 1978), reductions in the oxygen availability in the substrate due to infiltration or smothering of fines (Carling, 1984), reductions in fish growth rates and suffocation through clogging (Lake and Hinch, 1999).

In the UK, recognition of the negative effects of sediment loss into waterways has resulted in the regular assessment of water quality. Routine sampling is conducted as part the Environment Agency's General Quality Assessment (EA GQA) and the Harmonised Monitoring Scheme (HMS) (DEFRA, 2004). In some instances, these monitoring programmes have had success in providing estimates of the annual fine sediment transfer at the catchment outlet (Littlewood and Marsh, 2005). However, a lack of funding and poorly designed programmes have limited the benefits of this monitoring (United Nations Environment Programme and World Health Organization, 1996).

It is now accepted that higher resolution (i.e. at least hourly) and spatially extensive datasets on sediment quantity are now required in order to: more accurately estimate fine sediment flux in rivers (Owens and Collins, 2005), assess the magnitude and duration of exposure of aquatic organisms to suspended sediment (Bilotta and Brazier, 2008) and highlight areas within catchments responsible for the delivery of fine sediment to the channels. This is in part driven by the requirements of the Habitats Directive (1992) (COUNCIL DIRECTIVE 92/43/EEC) and the EU Water Framework (COUNCIL DIRECTIVE 2000/60/EC).

1.2 Research Statement

The aim of this research is to characterise the magnitude, timing and physical characteristics of fluvial fine suspended sediment transfer at a number of points distributed through the predominantly upland meso-scale catchments of the Esk and Upper Derwent using a novel research design. The assessment of two adjacent upland catchments at this scale will capture the complex suspended sediment responses to the spatio-temporal variability in climatic conditions, land use and soil conditions. This research has been designed to produce transfer rates of fine suspended sediment and characterise the physical properties of the transported material in each sub-catchment of the Esk and Upper Derwent catchment (where feasible). This is achieved through a highly distributed network of time-integrated suspended sediment sampling devices (Time Integrated Mass-flux samplers (TIMs) (cf. Chapter 5). Furthermore, an assessment of the dynamics of suspended sediment (SS) over multiple timescales and the determination of potential sediment sources will be achieved at three locations following the collection and analysis of high frequency suspended sediment data (cf. Chapter 6). These data are also used to develop empirical models for the purpose of predicting fine suspended sediment concentrations over the short term (cf. Chapter 6) and for testing the accuracy of distributed models as a means of estimating areas of fine sediment transfer (cf. Chapter 7). Furthermore, the analysed data can be used to inform future basin management plans, assess the water quality of rivers within environmentally sensitive areas and direct funds to areas where sediment flux is greatest (cf. Chapter 7). This will be achieved using the methodological framework shown in Figure 1.1.

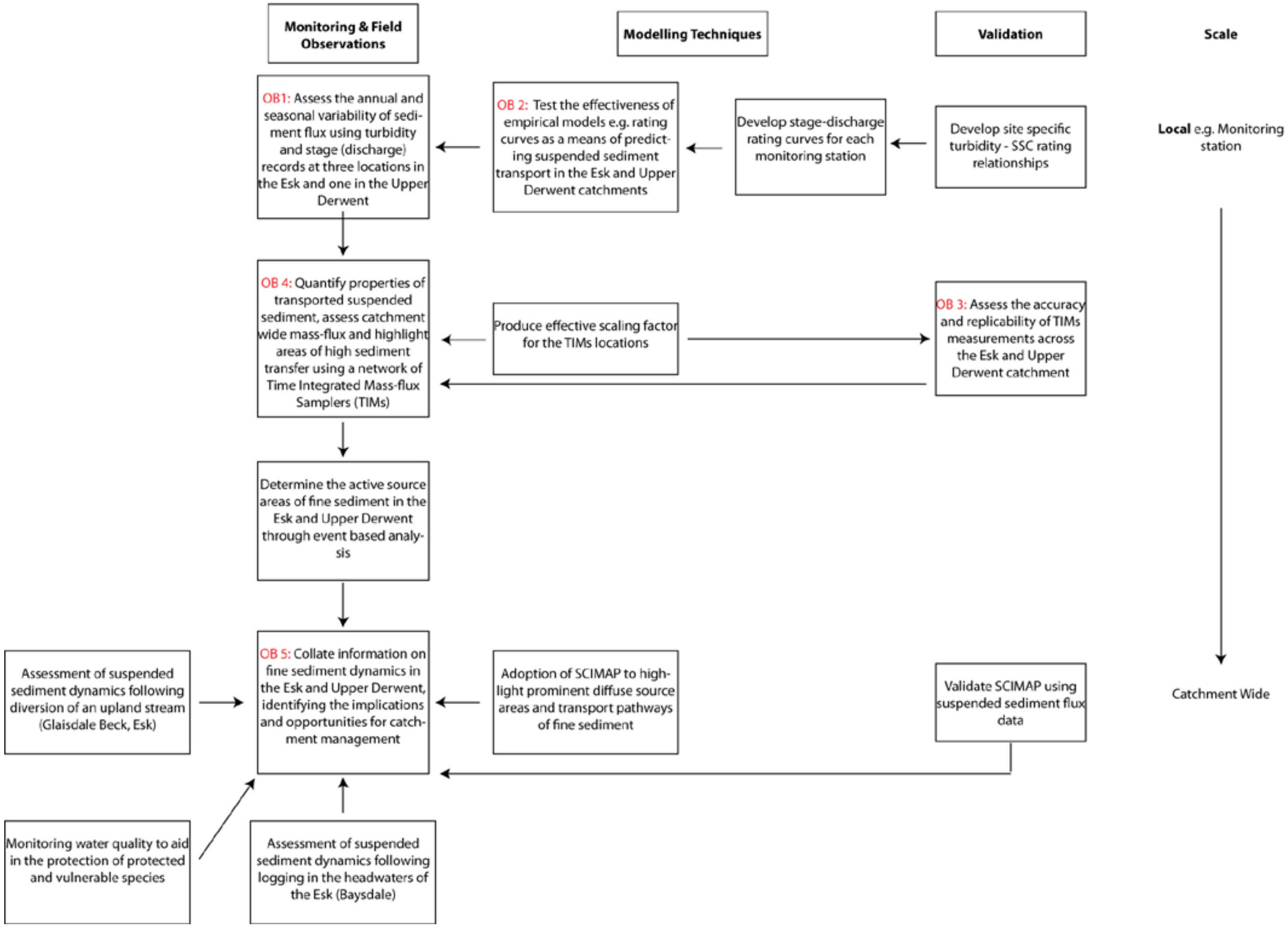

Figure 1.1: Adopted Methodological framework. OB *n* refers the reader to the associated objective.

1.3 Objectives

(1) Assess the variability of fine sediment dynamics at annual, seasonal, monthly and individual event time-scales at two sites in the Esk and one in the Upper Derwent catchment using turbidity and discharge records.

(2) Test the effectiveness of rating curves in predicting suspended sediment concentrations using flow data in the absence of continuous suspended sediment data.

(3) Trial new ways of capturing fine sediment transfer in upland UK environments i.e. test the accuracy and replicability of suspended sediment flux data generated by the networks of TIMs distributed in the Esk and Upper Derwent catchments.

(4) Assess the spatial variability in relative fine suspended sediment loads and assess the physical properties (i.e. absolute particle size, organic content) of the transported sediment throughout the catchments utilising TIMs.

(5) Using case studies evaluate the most effective means of assessing suspended sediment transfer in upland river catchments and identify the constraints and limitations of these approaches.

1.4 Thesis Structure

Chapter 2 begins by reviewing the current knowledge of fine fluvial suspended sediment transport in temperate environments. Discussion focuses on controls on suspended sediment yields, the highly episodic nature of sediment transfer and how the analysis of the sediment transfer dynamics can inform us about the availability and location of accessible sediment sources within the catchment. Available methods used to collect suspended sediment concentration/load data are discussed. Chapter 3 provides the background on the studied catchments, highlighting the physical properties of the area. Chapter 4 focuses on describing the methodology adopted and providing the justification for the approaches used. Chapter 5 presents results from the TIMs monitoring campaign, focussing on how the flux and properties of sediment vary across the catchments and also how these characteristics vary at each individual monitoring location. Chapter 6 presents detailed analysis of the temporal dynamics of suspended sediment transfer at key monitoring locations throughout the catchments using high frequency suspended sediment monitoring data. Chapter 7 utilises case-studies to highlight the application of this research and its methods and provides implications for management in the catchment. Chapter 8 is the conclusion which brings individual components of the thesis together and provides recommendations for furthering the research conducted as part of this thesis.

Chapter 2: Review of Fine Sediment Transfer in Temperate Fluvial Environments

2.1 Overview

This chapter provides an overview of current understanding of fluvial fine suspended sediment transfer with emphasis placed on temperate upland environments.

2.2 Key Terms and Definitions

In terms of sediment transported in rivers, the fine fraction incorporates the organic and mineral particles > 0.45 µm and < 2mm in diameter: this is known as the fine suspended sediment load. This suspended material accounts for the majority of flux of solid material eroded from the landscape, transported by streams, and deposited in sinks (Meade et al., 1990). The lower boundary (0.45 µm) provides the distinction between dissolved and solid material and is somewhat of an arbitrary guideline as defined by analytical procedures, whereas the upper boundary represents the boundary between suspended and bed-load material which may typically be transported close to the river bed (Owens, 2008). An additional distinction is also sometimes made between fine sediment and very fine sediment (< 62.5 µm). The latter is not controlled by hydraulic characteristics of flow, rather its occurrence is dependent on the upstream supply rate (Khullar et al., 2010). This is termed the 'wash load' and may constitute an important component of the particulate flux from terrestrial stores (Owens, 2008). This colloidal material may flocculate to produce much larger composite particles which can be extremely important in the transfer of pollutants and contaminants through river systems and have been highlighted as being responsible for the degradation of water-bodies (Droppo, 2001; Ongley et al., 1992).

The transfer of suspended sediment through river systems is usually assessed through measurement of the mass of sediment transported per volume of sediment-aqueous mixture, typically represented as mg L^{-1} or g L^{-1} in highly erodible environments. Given the known discharge of flow, a rate of transport in mass per unit time can subsequently be calculated, representing the flux of suspended material (usually in tonnes). In order to draw comparisons between catchments of varying sizes, the flux per unit contributing area (t km^{-2} yr^{-1}) is often presented. However, this classification has been criticised, with Parsons *et al*., (2006) arguing that if flux is to be scaled in a physically meaningful way, it should be done so by the potential contributing areas over the time-scale of interest. They continue to argue that since the majority of sediment transferred in the short-term is derived from the bed and banks of the channels and from alluvial and colluvial deposits, a more appropriate scaling factor would be the active channel length upstream of the point of interest. This concept of spatially restricted potential source areas has also been highlighted in terms of 'critical source areas' of fine sediment sources and associated pollutants within catchments (Fargas et al., 1997; Strauss et al., 2007). However, the variable nature of overland flow, storm runoff generation and sediment contributions on an event basis have also been highlighted (Walling, 1983; Kirkby, 1978).

2. 3 Sediment Flux in UK Rivers

The importance of understanding the dynamics of upland rivers and headwaters cannot be stressed too strongly (Bishop et al., 2008). These systems drain areas Less Favourable Areas (LFAs), beyond the limits of enclosed farmland which are often open, wild, empty and hostile environments accounting for approximately one-third of the UK land surface-cover (Fielding and Haworth, 1999). This is where the water meets the land, providing rich ecosystems of natural diversity (Meyer et al., 2007). They act to convey coarse sediment (> 2mm), fine sediment (< 2mm), nutrients, large woody debris, coarse and fine organic matter (Walling et al., 1997; MacDonald and Coe, 2007), which in-turn maintain habitat quality (Geist and Auerswald, 2007; Russell et al., 2001; Turnpenny and Williams, 1980), may result in chemical and biological pollution (Robinson, 1973), affect downstream flood defences (Sear et al., 1995), dam efficiency (Brandt, 2000), navigation routes (McCartney, 2005), and the aesthetic and potable quality of water (Robinson, 1973).

A major threat to the maintenance of all these processes and in ensuring the functional integrity of our river systems is that of terrestrial erosion and enhanced suspended sediment delivery to watercourses. Although in the upland areas of the UK, terrestrial soil erosion rates are relatively low in undisturbed catchments of grassland, undisturbed moorland and natural woodland (Fullen, 1992; Pimental et al., 1995), there is evidence of accelerated erosion rates in certain locations. For example, McHugh (2007) estimates that approximately 2% of upland England and Wales has soil degradation issues as a result of modifications in land use and the inherent sensitivity of these areas to change

This issue is particularly relevant in upland catchments due to their often small size, combined with the provenance of rill and gully networks, artificial drainage channels, steep valley slopes and the lack of well-developed floodplains meaning that modifications to the landscape or river system can produce rapid changes in the magnitude and source of suspended sediment transfer (cf. Burt et al., 1983; Gimingham, 2002; Heathwaite et al., 1990; Imeson, 1971; Longfield and Macklin, 1999; Mather, 1978; McHugh, 2000; Robinson, 1990; Robinson and Blyth, 1982b). However, a complicating factor is that although increasing terrestrial erosion rates provide important information on potential flux, in the short term, suspended sediment yields may not be of the same magnitude (Walling, 1983); an estimated 90% of the sediment eroded from the land surface is stored between the uplands and the sea (Meade, 1996). This disconnection in the supply – delivery system is largely driven by hydraulic disconnectivity resulting in fine sediment being trapped in foot-slopes, concavities and floodplains (de Vente et al., 2007; Walling, 1999). Particle size can also limit connections, with larger particles taking longer to travel (Parsons et al., 2004). Hence, there are complex linkages between initial erosion and downstream fine sediment yields (cf. Trimble, 1983). In the short term, the strength of these linkages is based on the intrinsic buffering capacity of the catchment (e.g. drainage density).

Worryingly, however, many rivers across the UK are in fact showing evidence of increasing and high concentrations of fine suspended sediment, and associated contaminants and pathogens due to the release of sediments from long-term storage (Newson and Sear, 1998; Owens and Collins, 2005). The additional pressure is being placed on these environments by the changing climate (IPCC, 2007), increased farming intensity as a result of demand for food stability (Tilman et al., 2002), encroachment of human activity and subsequent changes in land use and landscape management (Gordon et al., 2002) are all matters for concern.

In addition to the ecological and physical implications of increased sediment transfer already noted, there are also legal implications of enhanced delivery of fine sediment to watercourses. Catchments must reach the requirements of the European Union Water Framework Directive by 2015 (Water Framework Directive, 2000) which seeks to provide the aquatic environment protection from further decline through the integrated management of water quality, water resources and physical habitat through assessment and management at the river basin scale (Collins and Anthony, 2008b). The catchment is seen as being appropriate for characterising spatial variability of sediment sources, and temporary/long-term storage of sediment (Owens, 2005) and as such is the scale of focus for this research. The Directive strongly emphasises the need to judge “good ecological conditions” in terms of in-stream ecology (Moss, 2008). However, this is highly dependent on the value given to the organisms present in the environment and ideally requires precise guidelines to be produced for each catchment. This is a complex task given the specific dose-response relationship for individual species and has largely been overlooked. In its place, generic critical thresholds and targets are often cited. Cooper *et al.* (2008) propose a critical threshold for suspended sediment concentrations (SSCs) in which the average does not exceed 25mg L^{-1}. This may be an ambitious target itself. However, for example, in the Esk Catchment (North Yorkshire), this threshold would not be sufficient to provide “good ecological conditions” for the endemic, declining species of Pearl Mussel, which has a critical threshold of 10mg L^{-1} (Stutter et al., 2008). This highlights the need for the development of catchment-specific guidelines.

Additional physical (as opposed to ecological) metrics have also been proposed in the wake of suspended sediment yields (SSYs) being viewed as a key indicator of land use and catchment management (Minella et al., 2009). These SSY guidelines were developed by Cooper *et al*. (2008) for specific catchment typologies for the UK and are presented in Table 2.1:

Catchment Type	Target SSY (t km^2 yr^{-1}) (lower quartile)	Critical SSY (t km^2 yr^{-1}) (Upper quartile)
High wet and low wet peat	50	> 150
Low wet other	40	> 70
Low dry other	20	> 50
High wet and high dry other	10	> 20
Low dry and low wet chalk	2	> 2

Table 2.1: An overview of fine sediment yield targets and critical levels for hydro-topographic characteristics of the UK

For uplands in the UK dominated by peat moorland, the corresponding target threshold is 50 t km^{-2} yr^{-1} whereas the cited target for other upland areas is 10 t km^{-2} yr^{-1}. Rivers draining undisturbed catchments may typically have background suspended sediment yields in the region of 20 t km^{-2} yr^{-1} (Evans, 2006). However, the aforementioned land management changes have resulted in more typical suspended sediment yields range from 10 – 100 t km^{-2} yr^{-1} (Evans, 2006). Table 2.2 provides an overview of research documenting suspended sediment yields in the uplands of the UK. Where research has been conducted to assess the effects of management activity (for example afforestation), emphasis has been placed on the pre-disturbance SSYs. Examples are also limited to where flux is measured using traditional in-stream monitoring techniques. These studies were conducted in catchments with a range of land uses, ranging in size from 0.0042 – 11.68 km^2 with specific sediment yields which range from 1.1 t km^{-2} yr^{-1} in a small undisturbed moorland catchment to 112 t km^{-2} yr^{-1} in a small moorland catchment. It is clear that most research has been undertaken in small catchments (< 10 km^2), which are usually dominated by either mature forest (prior to cultivation), or peat moorland (prior to afforestation) (Soutar, 1989). By the very nature of the upland research, these studies have been conducted in remote locations producing SSYs generally less than 100 t km^{-2} yr^{-1}, which is typical of upland catchments (Walling and Webb, 1981). Little research has been conducted on the generation of SSY data in catchments > 10 km^2 in upland catchments of the UK.

Catchment	Monitoring Period	Catchment Area (km^2)	SSY ($t\ km^2\ yr^{-1}$)	Reference	Dominant Land use
Grt. Eggleshope Beck, N. Pennines	1980	11.68	12.1	Carling (1983)	Peat moorland
Severn	1995 – 96	8.70	15.91 & 14.59	Leeks & Marks (1997)	Mature Forest
Monachyle, Balquihidder	1983 – 85	7.70	39.2*	Johnson (1993)	Mature Forest
	1984 - 86	7.70	38	(Ferguson and Stott, 1987)	Moorland
Kirkton	1983 - 85	6.90	56.6*	Johnson (1993)	Mature Forest
Afon Hafren	1975 - 85	3.67	35.3*	Kirkby *et al.* (1991)	Mature Forest
	1995 - 96	3.67	16.1 & 23.08	Leeks & Marks (1997)	Mature Forest
Wye Cyff	1975 - 85	3.13	6.10	Moore & Newson (1986)	Grassland
	1996	3.13	5.34	Leeks & Marks (1997)	Grassland
Coalburn	1972 – 74	3.1	3.0*	Robinson & Blyth (1982a)	Undisturbed moorland
Hore, Plynlimon	1983 – 86	3.08	24.4	Leeks & Roberts (1987)	Mature Forest
Plynlimon, Wales	1983 – 84	0.94	66.08	Francis (1990)	Peat moorland
Nant Tanllwyth	1975 - 85	0.89	12.1*	Kirkby *et al.* (1991)	Mature Forest
	1995 - 96	0.89	24.26	Leeks & Marks (1997)	Mature Forest
Loch Ard	1987 – 90	0.84	56.0	Ferguson *et al.* (1991)	Mature Forest
Rough Sike	1962-63	0.83	112	Crisp (1966)	Peat moorland
	1997 – 2001	0.83	44.85 ± 1.8*	Evans & Warburton (2005)	Peat moorland

Caunant Ddu	1982 – 83	0.34	3.7	Francis & Taylor (1989)	Undisturbed moorland
Nant Ysguthan	1982 – 83	0.14	1.1	Francis & Taylor (1989)	Undisturbed moorland
Upper Wye Cyff	1980	0.04	2.8	Reynolds (1986)	Grassland
Wessenden Head Moor	1984 - 86	0.0042	55*	Labadz *et al.* (1991)	Peat moorland

Table 2.1: Suspended sediment yields for upland catchments in the UK. Grouped by land use type and sorted by catchment size. * Indicates an average annual SSY.

2.4 Spatial Understanding of Suspended Sediment Delivery

Understanding the sediment delivery process at the drainage basin scale remains a challenge in erosion and sedimentation research (de Vente et al., 2007). Schumm (1977) conceptualised the fluvial system in terms of a source – transport – sink continuum (Figure 2.1). Zone one represents the head of the basin (i.e. hillslope), where maximum erosion rates occur. Zone two is responsible for the transfer of sediment and water through the channel networks and into Zone 3; the alluvial channels and estuaries where the process of deposition dominates. Lane *et al*. (1997) argue that in sub-catchments which show a high degree of similarity (i.e. the scale ratio of lengths (l) is constant, the ratios of areas is proportional to l^2 and volumes is proportional to l^3), the occurrence of the source-transfer-sink dynamics proposed by Schumm (1977) could well be expected to be replicated over a range of scales. Hence, catchment area could be expected to be a significant control on the suspended sediment yields produced (Lane et al., 1997).

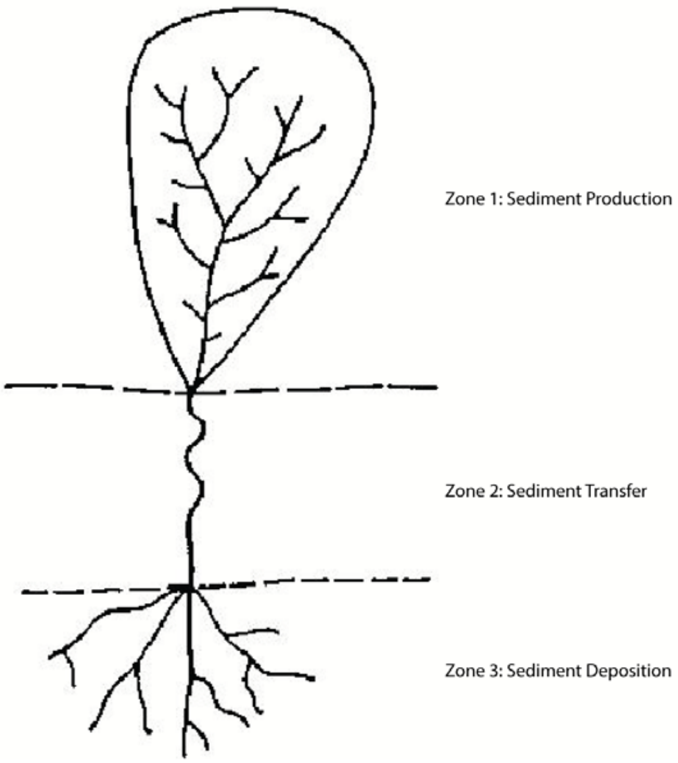

Figure 2.1: The Fluvial System (after Schumm (1977))

However, given natural variability in catchments (such as drainage density), it has been found that within, and between catchments, variations in SSYs exist. Figure 2.2 summarises the non-linear behaviour of SSY-area relations. It has been acknowledged that at a small scale (m^2), splash and sheet erosion are the dominant erosive processes (Osterkamp and Toy, 1997) which operate independently of scale; however as contributing area increases, more erosion processes become active e.g. rill, gully and channel erosion; leading to a rise in SSY. These peaks in SSYs have been found to occur throughout the range of $0.1km^2$ - $20km^2$ (Osterkamp and Toy, 1997; Chaplot and Poesen, 2012; Poesen et al., 1996) although this has been shown to be dependent on gully development, which in turn is dependent on local catchment characteristics e.g. slope (Vandekerckhove et al., 2000).

As the scale of the plot increases, increased heterogeneity of landscape features is expected. For example, decreases in local slope and the presence of wide floodplains can create sediment sinks (Walling et al., 1999; Syvitski et al., 2005; Birkinshaw and Bathurst, 2006), Furthermore, at the catchment scale, the effects of localised storms may become dampened; resulting in transport becoming greatly reduced (de Vente and Poesen, 2005; Lu et al., 2005; Birkinshaw and Bathurst, 2006). These catchment processes result in the inversion of the SSY-area relationship. This is consistent with the conceptual model shown in Figure 2.2 generated by de Vente *et al*. (2005) following a review of available research of SSY-area relationships.

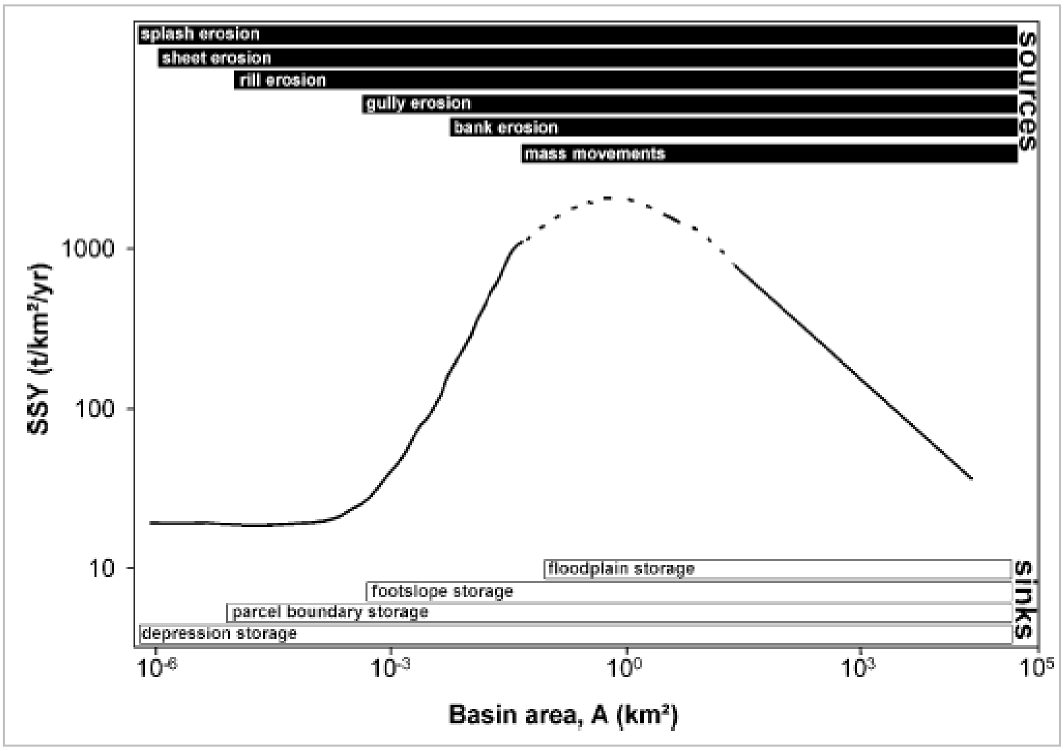

Figure 2.2: Conceptual model of SSY – area relationships (de Vente *et al*. (2005))

However, with a simple model such as this, the spatial heterogeneity of sediment sources, sinks and drainage density that one could expect between catchments means that there is little consistency in SSY-area relationships (Lane et al., 2007). These are important in ascertaining whether hillslope erosion is dominant over channel erosion or vice versa. Hillslope erosion (i.e. sheet and gully erosion) tends to dominate where there have been substantial modifications to the catchment (Dedkov, 2004; Walling and Webb, 1996). In this scenario, SSY is expected to decrease with increasing area due to particles being winnowed out of suspension and entering storage, without the river store being resupplied (de Vente et al., 2011).

Conversely when channel erosion dominates, SSY shows a continuous positive relation with area (Dedkov, 2004). This may also occur where headwater areas are characterised by resistant rocks and good vegetation cover but where the downstream areas are developed on softer, more erodible rocks (Walling and Webb, 1996), or where large volumes of unconsolidated sediment are available for erosion (e.g. Church and Slaymaker, 1989). Hence, spatial patterns in lithology, land cover, climate or topography can cause SSY to increase, decrease, or produce non-linear relations with area.

An additional consideration is the connectivity between eroding sources and the watercourse which will determine the effectiveness of hillslope erosion. This may be governed by the 'filter resistance' of a catchment, i.e. the strength of coupling between individual elements of the system and the consequent ability of the system to transmit kinetic energy (Burt, 2001). It may be lowered by high density road, track and field drain networks, or it may be increased by the presence of hedges, walls and buffer strips (Collins and Walling, 2004). Filter resistance can also vary temporally. For example, the presence of an exfiltrating water table on foot-slopes would produce saturation overland flow, thereby enhancing sediment delivery (Chaplot and Poesen, 2012). Of course, filter resistance is only maintainable in the short term. In basins that are operating close to equilibrium, over the long-term, the volume of eroded material must equate to the volume of erosion measured (Lu et al., 2005).

This section has documented the highly variable nature of SSY–area relations. Characterising this relationship across multiple scales within a catchment can provide information which will facilitate the understanding of catchment-wide sediment yield dynamics and provide an insight into the sediment delivery processes operating at different scales. This may be particularly powerful when used in conjunction with analysis of within-storm fine suspended sediment dynamics, which provide a direct means of evaluating the provenance of fluvial suspended sediment (Collins and Walling, 2004).

2.5 Within-Event Fine Sediment Dynamics

During a flow event, suspended sediment concentration is often not directly related to flow (Old et al., 2003) due to temporal shifts in the complex relationship between transport dependency and sediment availability. For example, Gao & Puckett (2011) found that during small events, sediment transport in streams was at capacity and dominated by the deposition process, whereas during large events, it was below capacity and controlled by the erosion process. As a consequence, the fluvial suspended sediment (SS) response can be highly variable for a given flow. An example of this can be observed during a rapid sequence of flow events, with latter events often producing lower SSCs, even though discharge is greater than the previous events (Eder et al., 2010). Globally, sediment transfer studies have highlighted the dominance of a 'first flush' and 'exhaustion' effect of suspended sediment transfer, whereby peak concentrations precede the peak in river discharge (Smith and Dragovich, 2009).

These complex non-linear responses during storm events can be investigated through the analysis of the timing of the SSC pulses relative to the river discharge (Hicks et al., 2000; Wolman and Miller, 1960). Deviations away from a linear Q – SSC relationship have been widely acknowledged with classification of the types of 'hysteresis' being achieved (Gregory and Walling, 1973; Arnborg et al., 1967; Paustian and Beschta, 1979; Wood, 1977; Walling, 1974). However, Williams (1989) was the first to compile a comprehensive account of potential hysteresis patterns. In this work, six common Q – SSC relations are classified. These are:

1. **A straight line**: The peak in SS concentrations occurs at the same time as the Q peak. The SS/Q ratio on the rising limb is equal to that on the falling limb (Figure 2.3 a).

2. **Clockwise loop**: The peak in SS concentrations precedes the peak in Q. The SS/Q ratio on the rising limb is greater than the same discharge on the falling limb (Figure 2.3 b).

3. **Anti-clockwise loop**: The peak in SSCs occurs after the peak in Q. The SS/Q ratio on the rising limb is smaller than the same discharge of the falling limb (Figure 2.3 c).

4. **Single line plus loop**: The SS/Q ratio on the rising limb is equal to that on the falling limb at low flow but at higher flows, a clockwise or anticlockwise loop may occur (Figure 2.3 d).

5. **Figure of eight**: A complicated relationship. A figure of eight with a clockwise loop occurs when SSCs rise rapidly with the peak preceding the Q peak (Figure 2.3 f). SSCs then rapidly fall at first before falling more steadily. #**6** The opposite is applicable for figure of eight with anticlockwise loop (Figure 2.3 e).

A summary of recent research on the analysis of within storm sediment dynamics and the occurrence of the hysteresis patterns observed is provided in Table 2.3.

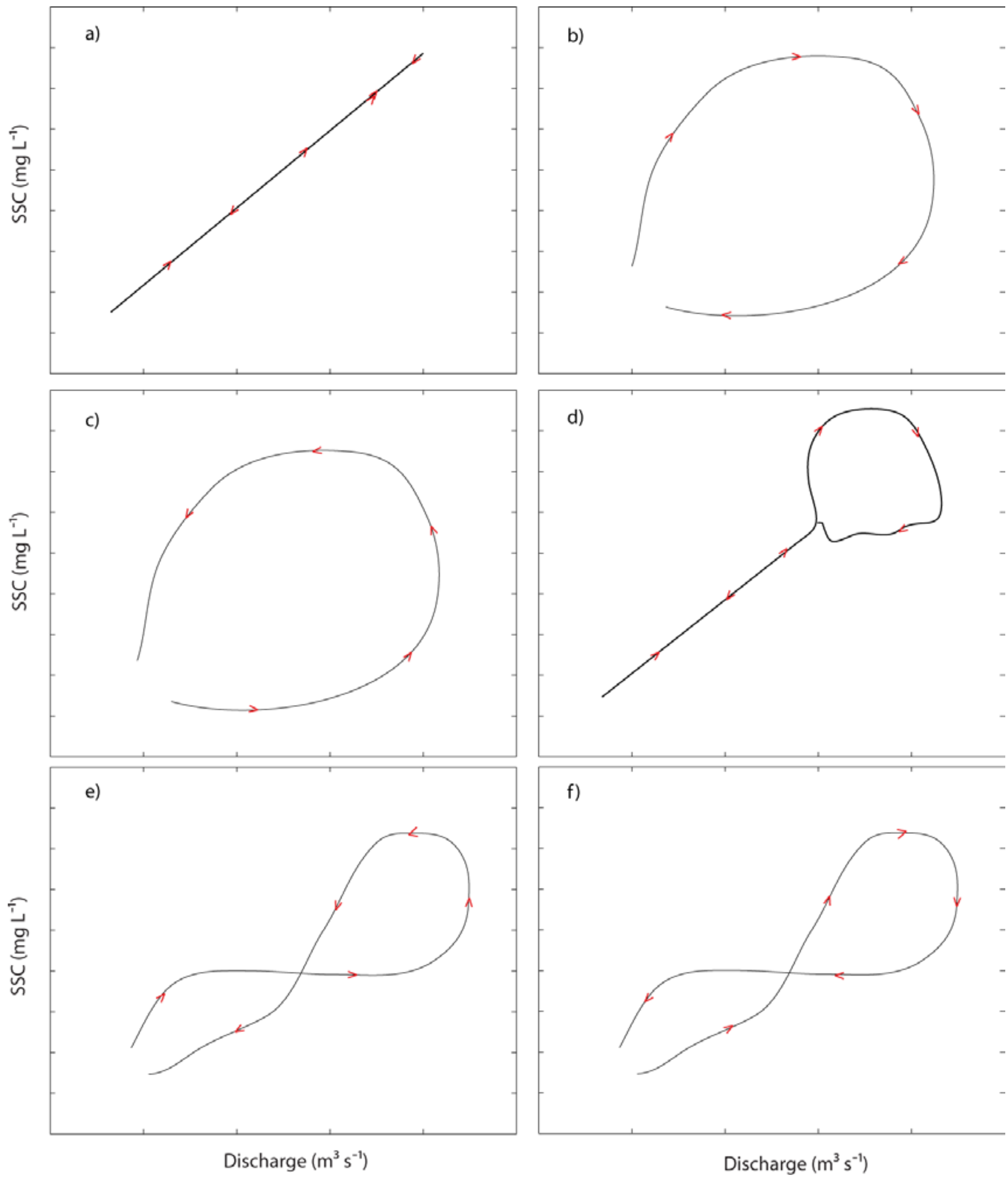

Figure 2.3 Schematic of fine suspended sediment hysteresis classifications after Williams (1989). **a)** No hysteresis; **b)** clockwise hysteresis; **c)** anti-clockwise hysteresis; **d)** single line plus clockwise loop; **e)** Figure of eight hysteresis with anti-clockwise loop; **f)** figure of eight hysteresis with clockwise loop

Catchment	Year of monitoring	Catchment Area (km^2)	Hysteresis observed	Reference
Rhine, Holland	1975 – 90	165 000	112 analysed events; Counter clockwise (18%), No hysteresis (17%), clockwise (55%).	Asselman (1999)
Coteaux Gascogne, France	2007 - 09	1110	68% of total sediment transport during all flood events demonstrated clockwise hysteresis, 29% anticlockwise and 3% simultaneity of SSC and discharge.	Oeurng *et al.* (2010)
Todera, Spain	1996 – 99	894	15 exhaustion floods (clockwise), 5 supply rich floods	Rovira & Batalla (2006)
Lachlan River, SE Australia	2005 - 06	1.64 & 53.5	73% and 74% of events in the sub-catchment and catchment respectively were clockwise. A further 14% were anti-clockwise in the sub-catchment with the remainder being random and figure-of-eight patterns	Smith & Dragovich (2009)
Arnás catchment, Spain	1997	28.4	12 events (63%) showed clockwise hysteresis, 3 (16%) were anti-clockwise with a further 4 (21%) having a figure-of-eight shape	Seeger *et al.* (2004)
Goodwin Creek, USA	1982 – 2001	21.4	Single peaked events account for 48% of high-flows. Of these, 84% are clockwise, 2% are anti-clockwise with a further 14% showing no hysteresis. Clockwise hysteresis also dominates the multi-peaked events	Salant *et al.* (2008)
Lake Tahoe, USA	2000	7.2	25 events (100%) exhibited positive hysteresis.	Langlois *et al.* (2005)
Petzenkirchen catchment, Austria	2006 - 08	6.4	Nine events (47%) showed clockwise hysteresis, whereas five (26%) showed a figure-of-eight relationship and just three (16%) anti-clockwise relationships.	Eder *et al.* (2010)

Rio Cordon, Italy	1991 - 96	5.0	4 events (50%) exhibited clockwise hysteresis, 3 (38%) showed anti-clockwise patterns, with 1 (12%) described as figure-of-eight.	Lenzi & Marchi (2000)
Virkosuo, Central Finland	2006 – 08	3.6	Anti-clockwise (48%), Clockwise (34%), random variations (10%) and figure-of-eight loops (7%).	Marttila & Kløve (2010)

Table 2.3: Summary of recent research into within-storm fine suspended sediment dynamics (listed by catchment area)

Analysis of the within-storm fine sediment dynamics allows inferences to be made about the processes responsible for the delivery and transfer of sediment to and from the channel, providing a useful tool for exploring sediment dynamics (Naden, 2010). However, determining what processes these within-storm sediment dynamics represent may be complicated by the variability in typology for a given process, especially in meso-scale drainage basins like the Esk and Upper Derwent, where SS dynamics may be sensitive to local sources such as bank collapse, concentrated sediment inputs from gullies, etc (Duvert et al., 2010). Despite these limitations, the assessment of hysteresis still provides a useful approach for assessing potential sediment sources within a catchment. Typical explanations for the hysteresis patterns include:

1. **A straight line**: An increase in the availability of SS is proportional to an increase in discharge (Q). This has been explained as a consequence of a constant supply of fine sediment available for transfer (Wood, 1977), with an absence of sediment exhaustion or time lags in sediment reaching the channel (Smith and Dragovich, 2009). It has also been suggested that the transport capacity of the river is the dominant control on transfer (Evans and Gibson, 2006). Large SS transfer events with no hysteresis may occur when a constant and abundant supply of material is available for transport, potentially as a result of soil surface exposure (Bača, 2008; Vongvixay et al., 2010), or infrequent events resulting in high levels of geomorphic activity (Eaton et al., 2010).

2. **Clockwise loop**: Clockwise loops can result from multiple environmental processes. It has been suggested that clockwise loops occur where the supply of SS is low (Williams, 1989). This is supported by some catchment studies (Marttila and Kløve, 2010; Seeger et al., 2004). However, a considerable body of research has identified that events characterised by clockwise loops are actually of considerable magnitude (Asselman, 1999; Rovira and

Batalla, 2006; Smith and Dragovich, 2009) with a high availability of sediment for transfer (Langlois et al., 2005).

A likely explanation for this is the 'first flush' phenomenon; whereby an initial peak in SSC occurs with relatively small increases in Q before sediment depletion of the readily available source results in a subsequent decline in SSCs, often long before any decrease in discharge (Salant et al., 2008). This implies that the available source of fine sediment is easy to mobilise and transfer and is likely to be proximal to the river channel (Bača, 2008; Lefrançois et al., 2007; Rodríguez-Blanco et al., 2010). These sediment sources include: bed material (Arnborg et al., 1967; Bogen, 1980), bank material (Lefrançois et al., 2007; Seeger et al., 2004; Smith and Dragovich, 2009) and foot-slopes which contribute first to discharge due to saturation excess overland flow (Mano et al., 2009). The degree of clockwise hysteresis may also be enhanced by sedimentation of suspended sediment shortly after the passage of the peak flood wave, which will be available for remobilisation during the rising limb of subsequent floods (Spott and Guhr, 1994). This can be observed during the passage of multiple peaked floods in quick succession. In this scenario, there is only a short time for sedimentation to occur, therefore, subsequent peaks in suspended sediment concentrations may be lower (Asselman, 1999).

In addition, the contrast in SSCs between the rising and falling limb may be exaggerated by the greater contributions of subsurface during the falling limb of the hydrograph (Bača, 2008). However, this cannot explain the sediment exhaustion typically observed prior to the peak in Q when a large proportion of Q is likely to be generated by overland flow and shallow subsurface pathways.

A final alternative for the occurrence of clockwise hysteresis is based on the assumption that rainfall at the start of an event is of greatest intensity and therefore produces a larger erosional force and detachment of particles (Doty and Carter, 1965). However, this is often catchment specific, as pronounced clockwise hysteresis can also occur following low intensity rainfall over a prolonged duration, thereby rendering the effects of intensity largely insignificant (Eder et al., 2010).

3. **Anti-clockwise loop**: The occurrence of anti-clockwise events is traditionally described as being a result of sediment derived from sources distal to the main channel (Eder et al., 2010) and may dominate when readily accessible sediment sources proximal to the channel are not present (Marttila and Kløve, 2010). This may explain why anti-clockwise events are sometimes associated with relatively low suspended sediment loads. However, research has also documented cases where events generating anti-clockwise hysteresis produce very high sediment loads (Seeger et al., 2004). These are generally highly active catchments with prolonged, high intensity rainfall and high antecedent soil moisture conditions. Thus there may be a combination of multiple mechanisms for the generation of anti-clockwise hysteresis.

   One specific theory is that prolonged rainfall will result in the expansion of the contributing area, capturing headwater zones of greater suspended sediment availability which are usually disconnected from main flow pathway (Bača, 2008; Marttila and Kløve, 2010; Webb and Walling, 1982). This may result in the transfer of high SSC flow reaching the main channel on the falling limb of the hydrograph.

   Alternatively, anti-clockwise hysteresis may be produced by the nature of conveyance of flow through a catchment. For example, dealyed contributions from headwater tributaries as a result of variations in rainfall patterns across the catchment may lead to a prolonged SSC signal (Rovira and Batalla, 2006). Or alternatively, the phenomenon of higher flood wave celerity compared to the flow velocity (which carries most of the SS) may result in the delayed arrival of peak SSCs relative to discharge (Williams, 1989).

4. **Single line plus loop**: The occurrence of this hysteresis type is based on the theory that at the beginning of the flow event, SSCs are transport limited with significant stores available. A clockwise or anti-clockwise component then occurs at peak flows as a result of depletion/increased availability of sediment stock. The Q – SSC relationship then falls to the same as that of the rising limb. This category is a combination of straight line hysteresis and clockwise, or anti-clockwise hysteresis (Morris and Fan, 1998).

5. **Figure of eight**: This is one of the rarer kinds of hysteresis found in catchment studies. There are two variations of this hysteresis; **a)** a clockwise loop at high Q or, **b)** an anti-clockwise loop at high Q. Although this type of hysteresis typically occurs relatively infrequently, they may be associated with very large flow events. Smith & Dragovich (2009) found that although clockwise events dominated the time-series, one figure-of-eight event was responsible for the transport of 86% of the annual sediment load. In this instance, an anti-clockwise loop at high Q was found, indicating the continued transfer of sediment through the system despite falling discharges. This type of figure-of-eight hysteresis appears to be the most frequently reported (cf. Eder et al., 2010; Seeger et al., 2004). This phenomenon has been attributed to the delayed contribution of a sub-catchment and the delayed connection of a significant sediment source (Eder et al., 2010).

From Table 2.3 it is clear that the majority of this recent research has been conducted in agricultural micro-scale catchments (1 – 100km^2) (as defined by Buras (1997)) with few in catchments > 100km^2. This lack of information at the meso-scale is where spatio-temporal variability in climatic conditions, land use and soil texture manifest themselves in the Q – SSC response (Oeurng et al., 2010). In these larger catchments, the examination of sediment hysteresis may be complicated by difficulties in deciphering between the erosive processes occurring and the timing and distribution of rainfall within the catchment. This complexity was highlighted by Bogen (1980) and subsequently by Mano *et al.* (2009), who found hysteresis patterns varied greatly between events in the Asse and Bléone watersheds (657 and 905 km^2 respectively). They believed this to be due to the distributed and varied sediment sources in the catchments. However, in the smaller Ferrand and Romanche catchments (82 and 230km^2 respectively), anti-clockwise events were observed during most storms. In the context of the Esk (286.57 km^2) and Upper Derwent catchments (236.33 km^2) (used for this study), the meso-scale drainage areas may pose some difficulties due to heterogeneous rainfall and timing of inputs from contributing tributaries.

In addition to this rather qualitative examination of the hysteresis present, attempts have been made to produce a quantitative estimate of storm event hysteresis. Langlois *et al.* (2005) produced a means of estimating this, whereby the SSC-Q regression equations were calculated separately for the rising and falling limb of the hydrograph. The area under the curve for the two regression equations was estimated through integration using the minimum and maximum discharge observed on the rising and falling limbs of the hydrograph. This method requires a high degree of correlation between Q and SSC on the rising and falling limb of the hydrograph ($R^2 > 0.90$) (Langlois et al., 2005), therefore potentially limiting its application. For example, Langlois *et al* (2005) were required to omit 14 out of 39 observed events due to failure to meet the required criteria.

Following this, Lawler *et al.* (2006) proposed a dimensionless hysteresis index (HI) for quantifying the non-linear behaviour by classifying the direction and magnitude of hysteresis present. The basic form of the hysteresis index quantifies the magnitude of variation between the SSCs at the mid-point of the event discharge (Figure 2.4). However, the HI can also be calculated for a range of discharge values, with the mean, and standard deviation being used to describe the non-linear behaviour throughout an event. This index has been used as a means of interpreting the spatial distribution of SS sources in a semi-arid catchment (Smith and Dragovich, 2009).

In order to calculate the HI, the mid-point of river discharge for the particular flow event is found and the associated suspended sediment concentration on the rising and falling limb are identified. When the SSC on the rising limb is greater than that of the falling limb (Figure 2.3 a) Equation 2.1 should be used to calculate the hysteresis index. However, when the SSC on the falling limb is greater than the rising limb (Figure 2.4 b), Equation 2.2 should be used.

$$HI = \frac{SSC_{RL}}{SSC_{FL}} - 1 \qquad \textbf{Equation 2.1}$$

$$HI = -1 \div \frac{SSC_{RL}}{SSC_{FL}} + 1 \qquad \textbf{Equation 2.2}$$

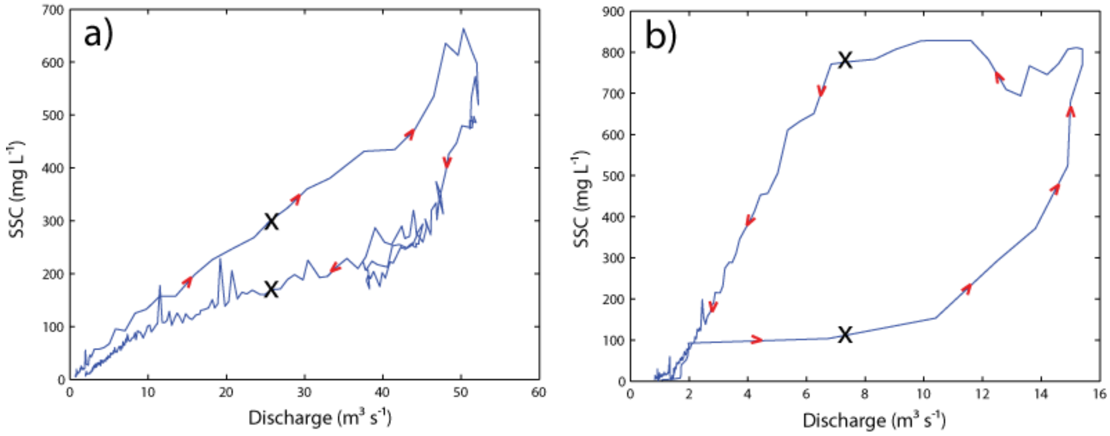

Figure 2.4: An example of within-storm sediment hysteresis directions. The **X** represents the mid-point of flow. This is the point at which the HI is calculated.

Both the qualitative and quantitative assessments of sediment hysteresis afford insights into the timing of sediment delivery. The approach attempts to assign an approximate sediment source and describe the delivery of fine sediment to the channel from the beginning to end of a singular mobilisation event.

Frequently, the analysis of within-storm fine suspended sediment dynamics is restricted to one point in a catchment i.e. catchment outlet. Complexities of within-storm fine sediment transfer at multiple scales have received far less attention. However, a recently developed methodology has enabled comparisons of the within-storm fine sediment dynamics at multiple sites for individual events. This method was developed by Smith & Dragovich (2009), whereby the degree of similarity between the patterns (and therefore erosive and transport processes across the catchment) are quantified. They term this the Similarity Index (SI) which can be calculated using Equation 2.3.

$$SF = A_R + LA_R \qquad \textbf{Equation 2.3}$$

where A_R is the ratio between the mean of all angles for the paired sub-catchment/catchment SSC – Q hysteresis patterns. LA_R is the ratio between the means of the multiplication of individual line lengths with their corresponding angles (Smith and Dragovich, 2009). The closer the SF is to 2.00, the greater the similarity between the sub-catchment/catchment responses. Their analysis showed statistically significant relationships between the SF and the peak catchment discharge, providing evidence for a "widespread event scenario", whereby proportionally similar discharges across the catchment as a result of widespread rainfall, results in comparable sediment dynamics across the catchment.

Catchments in the UK have not been subject to this kind of analysis, as sediment fingerprinting approaches are more widely adopted to categorise the sources of catchment sediment. Although this approach has been highly successful in ascribing sources (Collins and Walling, 1998; Collins and Walling, 2002; Collins et al., 1997b; Collins et al., 1997a; Collins et al., 1998; Collins et al., 2001), there are several limiting factors in its application:

(1) Its successful application is dependent on significant variability of chemical and physical characteristics of sediment within a catchment. In the context of this research, the relatively stable geology and land cover of the Esk catchment in particular would pose difficulties in differentiating between sources.
(2) Labour-intensive sampling campaign and laboratory analysis for a broad suite of constituents.
(3) The role in the environment of many of the constituents used in fingerprinting studies is poorly understood with respect to the extent to which they are conservative.

(4) The categorisation of within-channel suspended sediment as a separate class from other sources fails to appreciate this as a temporary store for sediment mobilised from the wider catchment in addition to being an ultimate source (Walling and Collins, 2008).

(5) The methods deployed to capture fluvial suspended sediment may bias sampling (see Annex A).

Hence, analysis of the within-storm fine suspended sediment dynamics is still a useful means of assessing the provenance of fine sediment. This method affords a more cost-efficient, direct means of assessing the zones of the catchment responsible for sediment delivery, whilst facilitating analysis on an event basis, at multiple scales throughout a catchment.

2.6 Controls on Suspended Sediment Particle Size

2.6.1 Introduction

In additional to characterising the dynamic flux of sediment transferred throughout river catchments, understanding the physical properties of fine sediment is important, specifically the discrete particle sizes which are most appropriate when assessing material fluxes, the size selectivity of rivers and in assessing the mobilisation and delivery of sediment in a catchment (Walling et al., 2000) which is the focus of this research. Sediment grain size is a fundamental property which controls entrainment, deposition and storage of fine sediment and provides insight into the erosion and transport processes in a catchment (Walling and Moorehead, 1987). This information is essential for accurately assessing the transfer of nutrients, contaminants and pollutants which may be readily adsorbed to silts and clays (Collins and Anthony, 2008a). This section introduces literature on the controls of suspended sediment particle sizes which is relevant to this research.

2.6.2 Spatial Variability

The composition of the transported fluvial sediments is primarily a product of; (a) the size distribution of surficial sediments; (b) the climatic controls on the weathering process; (c) the particle size selectivity of the sediment detachment and mobilisation process; (d) connection between potential source areas and the river network; (e) the particle size selectivity of the sediment delivery process and; (f) the opportunities for storage in the catchment and river network itself. Although important, the hydraulic properties of the river may in some respects be seen as a secondary variable in many fine-grained systems due to the excess capacity for sediment transport.

Ultimately, the size distribution of surficial sediments available for mobilisation on a hillslope is largely related to the underlying geology (Walling and Moorehead, 1989), which interacts with climate through bedrock weathering to produce the textural composition of eroded parent materials (Stone and Saunderson, 1996). The presence of moraines and glaciofluvial deposits (Bogen, 1992) and the deposition of coarse loess deposits (Ball, 1939) may also be controlling factors. The presence and interactions between these factors will govern the grain size distribution of sediment available to be mobilised across the landscape (Sable and Wohl, 2006).

Upon the generation of a soil with a specific particle size distribution, a given particle will be exposed to splash and wash detachment processes responsible for mobilisation on a hillslope. However, this process has been found to be highly size selective. It may be typical for the coarsest particles to resist detachment and transport by erosion because of their physical mass (Poesen and Savat, 1981), leading to enrichment of the eroded sediment by fine particles. For example, Young (1980) found that particles within the range of 20 – 200 μm were most likely to be eroded, with coarser particles resisting detachment. This is further highlighted by Stone & Walling (1997) who found that hillslope sediments < 60 µm were preferentially mobilised from the hillslope with larger material being left *in situ*. However, this is also complicated by the stabilising properties of clay materials over coarser fractions. For example, Ampontuah *et al.,* (2006) found that the presence of fine fractions (< 16 µm) in the soil generally increased with slope as result of the bonding structure of clay particulates, whereas the coarser fractions (16 – 63µm), were relatively easily detached and transported.

Following the detachment of eroded materials on the hillslope, connectivity between these isolated points and the river network is of importance. The likelihood of connection to a waterbody may be viewed as a function of the energy gradient (i.e. slope), topographic wetness index (i.e. propensity to generate overland flow), and downstream linkages to the channel. This is a dynamic process, responding to the antecedent catchment conditions.

Following the transfer of fine sediment from the wider catchment to the river network, in addition to the re-suspension of bed materials and erosion of bank materials, the subsequent movement of sediment may be viewed as a highly selective process which is influenced by stream gradient, bed-form configuration and hydraulic roughness. For example, Davide *et al*. (2003) found that with increasing distance downstream, suspended sediments became enriched in the clay fraction (0.4 – 4µm), whereas the bed material became coarser at that point. This was attributed to the longitudinal reduction of current shear velocity.

Anthropogenic activity may also be a significant control on particle size distributions. For example, Vaithiyanathan *et al*. (1992) found that the intersection of dams acted to disrupt the longitudinal pattern of delivery of coarse particles with the river thereby becoming enriched in fines. However, with increasing distance downstream of the dams, coarser particles gradually increased in abundance and began to dominate the suspended load of the river. A similar phenomenon was documented in the research presented and Ramesh & Subramanian (1988); however following the deposition of coarse particles, fine sediment dominated the transport regime through to the mouth of the Krishna river.

2.6.3 Temporal Variability

Size selective transport has been widely observed (cf. Old et al., 2003; Nordin, 1963; Walling and Moorehead, 1989; Carling, 1983) and occurs in instances where the flow is the dominant control on entrainment. However, in other river systems, sediment particle size has been found to remain constant, increase, decrease or exhibit complex relationships with discharge. This full range in responses was observed by Schäfer & Blanc (2002) in their study of six rivers in the South of France.

2.6.4 Regional Patterns of Suspended Sediment Particle Size

As a result of the combination of factors described above, significant differences between geographical settings are common. For example, Dedkov and Mozzherin (1984) highlighted the importance of geographical characteristics on the median particle size of transported sediments. For example, in the steppe and forest-steppe zones, median particle size was 64µm whereas in the tropical zone the median particle size was 34 µm.

Much of the research conducted in the UK has been focussed on lowland catchments, where the sediment transfer regime is largely made up of the clay and silt fraction i.e. < 62.5 µm (Walling and Moorehead, 1989). For example, Philips and Walling (1999) found that over 95% of the suspended sediment transported in the Exe basin was < 62.5µm in diameter. In the LOIS (Land-Ocean Interaction Study) basin of the Humber, the median particle diameter, averaged for all rivers, was found to be 7.58 µm with a mean of is 14.36 µm (Wass and Leeks, 1999). These sampling stations were located in lowland areas of the Tweed and Humber catchments with catchment sizes ranging from 499 – 4390 km^2 and are dominated by fine and clay-sized material. Across all catchments, the largest d_{50} measured was 9.18 µm in the Nidd whereas the smallest d_{50} was 4.06 µm, measured in the River Don. For all monitoring locations, the percentage < 63µm was greater than 92% (Phillips et al., 1999) .

Conversely, in the upland river basin the River Derwent (Lake District), the > 62.5µm fraction accounts for approximately 55%, 30%, and 30% of collected fine sediment in the Glenderamackin/Greta/Derwent catchment, Newlands catchment and Chapel Beck catchments respectively (Hatfield and Maher, 2008). This shows a distinct contrast to the typical sediment particle size distributions in the lowland rivers of the UK.

2.7 Organic Content

2.7.1 Introduction

On land, particulate organic matter (POM) comprises all soil organic matter (SOM) particles <2 mm and >53 µm (Cambardella and Elliott, 1992) and represents the accumulated, decaying debris of biota living on or in the soil i.e. the non-living organic component. In British rivers, however, the organic component of river suspended sediment typically accounts for less than 30% by weight (Hillier, 2001). Its occurrence in the river environment is complex and driven by multiple factors:

(a) Allochthonous terrestrial input from the drainage basin, which may be limited to infrequent events driven by the episodic pathways between the landscape and the river environment (Tockner et al., 1999), thereby operating as a supply-limited system (Walling and Webb, 1981; Bormann et al., 1974);

(b) Autochthonous production from within stream sources such as phytoplankton (Hedges et al., 2000), invertebrate faecal matter and diatoms (Egglinshaw and Shackley, 1971);

(c) The storage and degradation of this material during downstream transport (Evans and Warburton, 2005; Hopkinson et al., 1998).

2.7.2 Spatial and Temporal Variability

Research has found that fluvial transport of organic materials may be positively related with discharge, or the reverse (Brown, 1985) and highly temporally variable (Crisp and Robson, 1979; Grieve, 1984). Because of this variability, even intensive sampling regimes in headwater streams under-represent the transport of POM (Cuffney and Wallace, 1988). Therefore, time-integrated sampling may offer an alternative approach into estimating the particulate organic matter fluxes through river networks. This knowledge is important for several reasons:

(1) The organic component may form a significant part, and in some cases, even the majority of the suspended load (Ongley, 1982);

(2) The supply of organic material to rivers, particularly in headwater reaches has downstream implications on aquatic productivity and maintaining the heterotrophic efficacy of the riverine system (Battin et al., 2008; Cummins, 1973);

(3) The presence of organic matter in river environments is important for the conveyance of nutrients, organic pollutants and sorbed contaminants such as phosphorus (Granger et al., 2007; Ongley, 1982; Haygarth et al., 2006; Haygarth et al., 2005);

(4) Grassland areas of the piedmont zone (such as that found in the lower reaches of the Upper Derwent catchment) may be significant sources of organic material (Bellamy et al., 2005) as a result of excreta and recycled animal manure inputs, along with contributions from decay of the grass sward. The explicit assessment of these inputs has recently been called for (Brazier et al., 2007);

(5) Organic matter typically consists of ~50% organic carbon (Ball, 1964; Hedges et al., 2000) which represents the largest store of active terrestrial carbon, estimated to be 9838 ± 2463 × 10^{12} g in the UK alone (Dawson and Smith, 2007). Although particulate organic carbon usually only comprises about 10% of the total organic carbon transported (Hope et al., 1994), the ever increasing development of carbon management programmes require information about particulate carbon flux.

Previous research in the upland catchment of the Plynlimon (which is dominated by shallow blanket peat) found that over 50% of suspended sediment was organic material (Francis and Taylor, 1989; Francis, 1990). Furthermore, Labadz *et al.* (1991) found a considerable proportion of organic content in their study of upland catchments in the Pennines of England. The mean organic content across the four study areas ranged from 7.0 % - 38.18 %. Meanwhile, in a study of lowland catchments in the SW of England, the mean organic carbon content of the suspended sediment collected from each of the 10 study areas ranged from 4.5 to 12.2% (Ankers et al., 2003).

Temporal variability in the transfer of organic material has also been observed. For example, Ankers *et al*. (2003) observed organic carbon transfer peaking in summer and early autumn, which was attributed to increased primary productivity given the higher temperature and the change in balance of sediment sources, whereas Walling & Webb (1987) found that the organic matter content of sediment peaks during summer due to the influence of autochthonous sediment sources and the occurrence of lower flows which could be expected to be relatively enriched in POM due to its lower density (Hillier, 2001). Additionally, organic carbon has also been observed to decrease during storm events (Hillier, 2001) and is therefore lower during the winter months.

2.8 Measures of Suspended Sediment Flux

2.8.1 Introduction

In order to determine the suspended sediment load of a river (SSL), two parameters are essential.

$$SSL = K \sum_{i=1}^{n} C_i Q_i$$ **Equation 2.4**

where C_i and Q_i are the instantaneous values of suspended sediment concentration and discharge respectively at the time of sampling, n = the number of samples and K is a multiplication factor to take into account the interval between samples.

The Q_i element of the equation is relatively accessible in most larger drainage basins of the UK given that the EA currently maintains over 1000 gauging stations. These stations typically collect high frequency flow measurements recorded at 15-minute intervals. However, suspended sediment concentration data are somewhat more difficult to acquire given the lack of well-equipped sediment monitoring schemes in the UK. Where monitoring schemes do exist, their ability to accurately collect good quality suspended sediment data is largely dependent on two key issues.

(1) The choice of method which is used to acquire the suspended sediment concentration samples; and,

(2) The subsequent laboratory techniques can have significant implications on the suspended sediment concentrations and therefore the suspended sediment loadings.

There are several commonly used methods for generating suspended sediment concentration data, which range from simple, direct and manually operated techniques to more complex, indirect and automated methods.

2.8.2 Direct Approach

Perhaps the most effective and direct means of obtaining suspended sediment concentration samples is by manual sampling of the river. This method requires the user to be able to directly submerge a bottle/sampling apparatus, into the flow of the river. Using this sampling method, it is often difficult to achieve good temporal resolution over the course of a year, with the number of samples being dependent on the proximity of the study area, financial and time restraints associated with travel. This sampling method also fails to produce an isokinetic, depth and width-integrated sample, bringing into question the representativeness of the sample. However, it may still produce representative samples in shallow, well mixed streams, where the suspended sediment is uniformly distributed along the vertical and horizontal planes (Sheldon, 1994).

A method of accounting for the variation of suspended sediment concentrations in the horizontal profile is to take measurements at several locations across the cross-section and determine the relation between the average and the point at which sampling is undertaken. A coefficient can then be produced to convert the fixed sample to the mean cross sectional value (Horowitz, 1995). Alternatively, this information can be used to determine the most adequate location for a fixed sampling station (Porterfield, 1977). However, this coefficient is unlikely to be constant, becoming modified with changes in bed forms, source and type of sediment. Given that sampling across a flow section may not feasible (Abtew and Powell, 2004) and the potential complexity and time consuming nature of assigning coefficients to the monitoring stations, correction procedures are not always used.

Given the vertical and horizontal variability in suspended sediment concentrations (> 63µm) that often exist in rivers, it has been recommended that depth-integrated sediment sampling is undertaken across the channel using suitably designed equipment (Wass and Leeks, 1999; Horowitz et al., 1990). Depth-integrated samplers (e.g. D-77 or DH-81) provide vertically representative samples when they are lowered to the stream bed and raised at a uniform rate. Alternatively, representative samples may be gained using point-integrating samplers (e.g. P-46 or P-61). This is achieved by opening a valve and moving the sampling device through the stream vertical (Vanoni, 2006). The difference between the concentrations generated by single point sampling and a depth-integrated average were shown to differ by 2% and 12% in the Rivers Ure and Aire respectively, but did not differ significantly in the River Ouse (Wass and Leeks, 1999).

Suspended sediment sampling has been made significantly easier following the widespread commercial availability of automatic water samplers. These consist of an intake, sample distributor, pump, bottle container unit and activation system (Gray et al., 2008), whereby a sample volume which is dependent on the peristaltic pump (or vacuum) speed and number of rotations is drawn up from the channel by suction (Newburn, 1988). These samplers began as basic instruments (Walling and Teed, 1971) and have become complex, efficient, lightweight, affordable and computer controlled, allowing sampling to be triggered remotely or initiated automatically in response to rainfall, or changes in river flow/level. This remote activation has generally enabled greater precision and frequency of sampling during storm events as a result of reduced sampling costs. As with direct manual sampling, most pump sampling equipment takes samples at a single point in the river cross-section, resulting in similar issues of representativeness. However, positioning the sampler intake at a fixed position at 60% the stream depth may minimise this and provide the most representative sample (Newburn, 1988). Although modifying the sampler intake location as river depth fluctuates may be problematic. Pump samplers have been shown to operate best in fine grained fluvial environments (Lewis and Eads, 2008) due to the samplers' inability to collect samples isokinetically. Where sand-sized material is in transport, the particle size distribution and amount of sediment collected may be compromised (Bent et al., 2001). However, samples have been shown to be comparable with those derived using manual sampling methods (Graczyk et al., 2000).

2.8.3 Sampling Framework

An additional determinant on the quality of suspended sediment flux data is the sampling scheme which is adopted. The chosen scheme must be able to maximise precision in the suspended sediment flux estimates, whilst being cost-effective. This is a difficult balance to attain given that confidence intervals of estimates may be viewed as a function of the number of samples (Dixon and Chiswell, 1996). In order to maximise the efficiency of monitoring campaigns, numerous different sampling strategies have been developed. Some of the more widely used monitoring frameworks are introduced here.

Time-proportional sampling involves the continuous sampling of the river in uniform time steps which are proportional to the available analytical funds, availability of time for collection and sampling apparatus. Sampling may be discrete i.e. one sample per bottle, or composite i.e. multiple samples per bottle. If the time step is sufficiently short (i.e. sub hourly) then this may be an appropriate method (e.g. Leecaster (2002)). However, it is often not technically feasible to continuously sample suspended sediment concentrations over a prolonged period whilst maintaining a short and constant sampling interval. When the time step is increased, deviations between the true and estimated loads develop. It has been observed that the use of weekly and monthly suspended sediment concentrations as a means of predicting sediment loads can produce estimates of between 20.1 - 107.8 % and 12.5 - 110.3 % of the annual reference flux respectively (Phillips et al., 1999) whereas daily sampling programs may be accurate to within 5%, or as much as 50 – 200% of the true annual suspended sediment loads (Colby, 1956). From these examples it is clear that the error in obtaining suspended sediment loads using time proportional suspended sediment sampling can be considerable and it is rarely an accurate means of quantifying the sediment loads.

In order to reduce the error using time proportional frameworks, numerous estimators have been developed and adopted in order to best quantify the suspended sediment loads from infrequent SSC data. A suite of methods are classed as averaging (or interpolation) procedures. These assume that the collected data are representative of the river at times where transfer is not recorded. Some of these methods are introduced here Equations 2.5 – 2.8) and an exhaustive assessment procedures can be found in Phillips *et al.* (1999):

$$Total\ Load = K\ \left(\sum_{i=1}^{ns}\frac{Ci}{ns}\right)\left(\sum_{i=1}^{ns}\frac{Qi}{ns}\right)$$ **Equation 2.5**

Equation 2.5 signifies that the total sediment load over the monitoring period can be estimated by multiplying the mean of the sediment concentrations by the mean river discharge measurements. There is no assumption that the SSC and discharge measurements have to be paired, whereas in Equation 2.6 this assumption is implicit.

$$Total\ Load = K\ \sum_{i=1}^{ns}\left(\frac{Ci\ Qi}{ns}\right)$$ **Equation 2.6**

The total load is calculated in Equation 2.7 through the product of the instantaneous suspended sediment concentration data points with the average discharge over the period between SSC samples (Q_p):

$$Total\ Load = K\ \sum_{i=1}^{ns}\left(Ci\ Q_p\right) \qquad \textbf{Equation 2.7}$$

The total load is calculated in Equation 2.8 by multiplying the average SSC over the time period by the mean discharge for the entire period of record (Q_r) :

$$Total\ Load = K\ \left(\sum_{i=1}^{ns}\frac{Ci}{ns}\right) Q_r \qquad \textbf{Equation 2.8}$$

The efficiency of these algorithms was evaluated by Walling & Webb (1985). They found that using these estimators in conjunction with weekly sampling of suspended sediment concentrations produced load estimates which ranged from 65% and 200% of the actual load, with monthly samples producing load estimates between 5% and 250% of the actual load. Error associated with these load estimators may be attributed to implicit statistical assumptions such as the data are independent and identically distributed, which are rarely met (Preston et al., 1989) due to extensive gaps in the suspended sediment record and preferential sampling under low flow conditions (Gray and Simões, 2008).

Flow-Proportional sampling is a frequently adopted method in which samples are taken at regular flow volume intervals. The interval is often predetermined using historical flow data. Upon a cumulative threshold volume being met, a signal is sent to the auto sampler to initiate collection. This approach may be justified where strong correlations between discharge and suspended sediment concentrations are found. An example of this scenario was observed in the Santa Ana basin during the 1997/98 hydrological year when flow accounted for 40% of the variability in suspended sediment concentrations (Leecaster et al., 2002). Using this approach, both discrete and composite samples can be collected. Whilst discrete, flow-proportional sampling has been found to produce better estimates of loadings over spot, grab samples and systematic sampling (de Vos, 2001), flow-proportional composite samples may yield even better load estimates given the potential to take a greater number of sub-samples under storm conditions (Braskerud, 2001).

Probability sampling of suspended sediment concentrations is a frequently adopted means of estimating the sediment load of the river. The probability of a sample being taken can be constant e.g. simple random sampling. Although, this is likely to grossly underestimate the suspended sediment load due to the probability distribution of the flow being positively skewed, whilst the majority of suspended sediment is transported under high-flow conditions. Alternatively, the probability can be varied in response to knowledge about under what conditions suspended sediment transfer is most likely to occur (Thomas and Lewis, 1995; Littlewood, 1992). It is known that up to 50% of the total suspended sediment load can be transported in as little as 1% of the time, and 90% transported in under 5% of the time (Walling et al., 1992) so therefore sampling protocols have been developed which utilise this knowledge.

An example of such a programme is Selection-at-list-time (SALT) sampling. This is a variable probability sampling method which utilises an auxiliary variable (such as river flow), which is positively correlated to the square of the primary variable divided by the auxiliary variable (Thomas, 1985). The auxiliary variable might be a stage based prediction of unit yield from a sediment rating curve (Thomas and Lewis, 1995). As such, sampling is largely limited to relatively infrequent storm events. However, in recent years, the use of these auxiliary variables has been expanded. The Turbidity Threshold Sampling (TTS) method

(Lewis, 1996; Lewis, 2003; Lewis and Eads, 2001; Lewis and Eads, 2008) utilises turbidity as the auxiliary variable. When the defined turbidity condition being met, suspended sediment samples are taken. This development has been deemed necessary given that suspended sediment concentrations can fluctuate independently of water discharge during high-amplitude sediment pulses (Lewis and Eads, 2008), with more accurate constituent load estimates generated than those whereby discharge has been used as the trigger .

A related approach which utilises *a priori* knowledge is that of **stratified sampling**. Sampling can be both time and flow stratified. With time stratified sampling, the hydrograph is divided into different time length periods. The length of these time lengths is predetermined. During periods of longer, low flows, the stratum length is increased, resulting in fewer samples being taken whereas during rapidly increasing levels, the strata will be shortened resulting in more samples being taken per unit time (Thomas and Lewis, 1993; Thomas and Lewis, 1995). The premise being that during the low-flow periods, variance will be lower and therefore fewer samples required. The inverse is the case under high-flow conditions. At the beginning of each stratum, the stage direction and river level is determined, the stratum length is assigned and sample times are randomly assigned. The accuracy of suspended sediment flux estimates over the monitoring period is dependent on the magnitude of variance during each stratum. This is, of course, a direct result of how appropriately the stratum lengths are assigned beforehand (Thomas and Lewis, 1993; Thomas and Lewis, 1995). This sampling method has been shown to obtain suspended load estimates with coefficients of variation between 1.4 and 7.7 times less than those derived from SALT sampling (Thomas and Lewis, 1995). The main difference with flow stratified sampling is that the hydrograph is stratified by water discharge rather than time. The range of flow is divided into classes by stage height and direction and each flow class is randomly sampled during the time it is occupied (Thomas and Lewis, 1995).

In instances where it is not practicable to sample all or the majority of sediment transport events, regression methods may be deemed appropriate. These methods have the potential to yield relatively accurate estimates of suspended sediment discharge for a given flow (Asselman, 2000; Horowitz, 2003; Sadeghi et al., 2008; Walling, 1977). Extrapolation methods for predicting suspended sediment discharge (Q_s) commonly take the form:

$$Q_s = f(Q) + \delta$$ **Equation 2.9**

Or

$$SSC = f(Q) + \delta$$ **Equation 2.10**

$$Q_s = K \cdot SSC \cdot Q$$ **Equation 2.11**

Of the two extrapolation methods stated above it has been shown that the $Q_s - Q$ relation produces higher correlation coefficients than the latter method using the $SSC - Q$ relation (Achite and Ouillon, 2007). It has been argued that these are artificially high correlations as a result of Q being a component of both the dependent and independent variables and therefore introducing bias in the relation (McBean and Al-Nassri, 1988). However, this has also been contradicted (Annandale, 1990; Nordin, 1990; Milhous, 1990), with these discussions indicating that the use of $Q_s - Q$ does not yield significantly different sediment load estimates to those using the $SSC - Q$ relation. However, (Kenney, 1982) warned against correlating variables with common terms due to the possibility of spurious correlation. Subsequently, the $SSC - Q$ relation is viewed as a more robust method since no additional error is introduced when the observed Q is multiplied by SSC estimates to produce Q_s. As such, this is the most widely used extrapolation procedure for the estimation of fluvial sediment load. The success of this extrapolation procedure is highly dependent on the sampling regime. In order to yield the most representative estimates of Q_s, SSC measurements should be taken at known discharges across the full range of flow conditions, with large sample sizes and small sampling intervals (Ferguson, 1987).

Although this approach is widely used (Asselman, 2000; Ferguson, 1986; Horowitz, 2003; Sadeghi et al., 2008), significant errors are often inherent in basic regression models as a consequence of systematic errors associated with suspended sediment concentration and river discharge measurements, or as a result of the non-linear relationship between the variables which may be caused by seasonal effects, antecedent conditions, the availability of sediment during an event and varying tributary inflow (Asselman, 2000; Walling, 1977). Despite these general limitations, the use of rating curves and more specifically, power functions are widely adopted as a means of estimating the suspended sediment flux of a river. These power functions take the form of Equation 2.12.

$$SSC = aQ^b \qquad \textbf{Equation 2.12}$$

where $a \text{ and } b$ are empirically drived coefficients and Q is the instantaneous river discharge (m^3 s^{-1}). The solution to this power function may be obtained using non-linear regression and an additive error value, δ which is random, normally distributed, with zero mean and variance:

$$SSC = aQ^b + \delta \qquad \textbf{Equation 2.13}$$

Slight modifications of this initial power function solved using non-linear regression have also been proposed. Asselman (2000), suggests the use of an additive constant element (p), which effectively acts to shift the rating relationship:

$$SSC = p + aQ^b + \delta \qquad \textbf{Equation 2.14}$$

However, fitting the power law using non-linear regression may not be appropriate since homoscedasticity (the assumption of constant variance or scatter of the dependent variable) is often not met due to the scatter of sediment concentrations against discharge usually increases with discharge. As such, a procedure used more frequently is to log-transform the SSC and discharge data, from which the regression coefficients a and b may be obtained by ordinary least squares linear regression:

$$\mathrm{Log}SSC = \log a + b \cdot \log Q + \log\varepsilon \qquad \textbf{Equation 2.15}$$

By transforming the data so that the trend is linear in log-space, the regression slope can be back-transformed into original units, producing an exponential fit, whilst ensuring that the residuals are normally distributed (Helsel and Hirsch, 1992):

$$SSC = aQ^b\, \varepsilon \qquad \textbf{Equation 2.16}$$

where ε is a log-normally distributed error.

Despite some of the statistical issues being accounted for, additional errors are often induced due to statistical inaccuracies of the method, specifically as a consequence of logarithmic transformation tending to favour points close to the origin (Sadeghi et al., 2008). This commonly causes suspended sediment loads to be underestimated (Asselman, 2000; Ferguson, 1986; Walling and Webb, 1988), but on occasions has also been shown to produce elevated estimates (Sadeghi et al., 2008). In response to the issues of over/under prediction, correction factors have been proposed that seek to account for the bias created. A frequently adopted correction factor is that proposed by Ferguson (1986):

$$CF = \frac{1}{n}\sum^{n} 10^{e} \qquad \textbf{Equation 2.17}$$

$$e = logC_{obs} - \ logC_{est} \qquad \textbf{Equation 2.18}$$

where C_{obs} is the observed sediment concentration and C_{est} is the estimated concentration for the same observation. Ferguson's (1986) correction factor has been widely used and has been shown to produce lower sampling variability than other correction methods when data are normally distributed about log-linear trends (Ferguson, 1987). However, this approach may not be appropriate when homoscedasticity is not met and the residuals are not normally distributed (Asselman, 2000; Smith and Dragovich, 2008). Alternatively, the Duan (1983) smearing factor which does not assume normality in the residuals and is the most widely used correction factor for small samples (i.e. < 10) (Helsel and Hirsch, 1992). This takes the form of:

$$CF = \exp\,(2.651\, s^{2}) \qquad \textbf{Equation 2.19}$$

where s is the mean square error:

$$s^{2} = \ \sum^{n} \frac{(logC_{obs} - \ logC_{est})^{2}}{(n-2)} \qquad \textbf{Equation 2.20}$$

When either of the Duan (1983) and Ferguson (1986) correction factors are adopted, the rating curve method is modified using Equation 2.21:

$$SSC = aQ^b\ (CF) \qquad \textbf{Equation 2.21}$$

Both of these bias correction factors and based on the residuals of the regression in log-transformed space, which are subsequently back-transformed. Therefore, in instances where the back-transformation has produced elevated estimates (cf. Sadeghi et al., 2008), the aforementioned correction factors cannot adjust the suspended sediment loads accordingly since they only allow for positive corrections (Kao et al., 2005). Therefore, Kao (2005) presented an alternative, whereby the residual error (ε) of the rating curve is firstly calculated in normal space, from which the correction factor of non-log transformed units (β) can be calculated:

$$\beta = \frac{\sum_{i-1}^{N}(\varepsilon_i)}{\sum_{i-1}^{N} f(Q)} \quad i = 1\ to\ N \qquad \textbf{Equation 2.22}$$

This correction factor can be positive or negative and be incorporated into the suspended sediment concentration estimate ($\widehat{SSC}$):

$$\widehat{SSC} = (1 + \beta) \cdot aQ^b \qquad \textbf{Equation 2.23}$$

Despite the simplicity and comparability of these models allowing the general comparability between research projects (Cox et al., 2008), the success of their application to the prediction of SSCs and sediment loads has been somewhat mixed and is largely dependent on the nature of the sediment supply and efficiency of delivery to the river channels. Bilotta *et al.* (2010), in a study assessing the erosion of a small, 0.46 km^2

catchment concluded that discharge was a poor predictor of suspended sediment concentrations (R^2 = 0.35) and therefore provided highly uncertain sediment yields.

Consequentially, more complex approaches to rating curve development have been proposed as a means of better explaining the variability and have been deemed appropriate for use in specific situations. Rating curves developed using second and third order polynomial regressions of log-transformed SSC and discharge have been shown to provide an appropriate means for explaining suspended loads producing annual estimates with errors < 15%, even without the use of a correction factor (Horowitz, 2003; Horowitz et al., 2001). Smith & Dragovich (2008) found that the adoption of polynomial functions in log-log space produced Nash & Sutcliffe (1970) R^2 values of 0.69, whereas the linear and linear corrected with Duan (1983), or Ferguson (1986) methods produced R^2 values of 0.37, -0.81 and -0.75 respectively, indicating that the polynomial function was the most efficient model in this particular application in headwater catchments of SE Australia.

In addition to these statistical means of producing better predictions of suspended sediment loads, other approaches have also been adopted which account for short-term and seasonal changes in the discharge – SSC relationship. This is achieved through the development of multiple rating curves which are adopted under specific conditions. For example, in highly erosive environments where the relationship between flow and sediment concentration rapidly changes, developing individual rating curves for different seasons, or pre and post events may be improve sediment load estimates (Kao et al., 2005). Alternatively, rating curves can be developed which focus on the highest quantities of flow and concentrations, producing truncated rating relations which may be more accurate at higher flows than traditional rating curves using all of the data points (Meybeck et al., 2003). Truncated rating curves were also deemed most applicable by Córdova & González

(1997) who created separate equations for flow above and below $19m^3\ s^{-1}$. Producing rating curves for the rising and falling limbs of hydrographs may also improve predictive ability. For example, Walling (1977) found that the error associated with a single rating curve ranged from 27.2 – 63.5%, whereas when the data were stratified by season, error ranged from 15.1 – 61.0%. Stage distinguished ratings further reduced the error to 4.0 – 30.7%.

2.8.4 Time- integrated Sediment Sampling

The methods that have been discussed so far are accurate at determining instantaneous suspended sediment concentrations but their ability to determine suspended sediment loads is limited by their inability to accumulate sediment samples over longer intervals. A potential means of overcoming this issue is to deploy time-integrated sampling apparatus. According to Nelson & Benedict (1951), these sampling devices should be:

- Isokinetic
- Pointed into the flow
- Protrude upstream of the area of disturbance
- Should be movable and suitable for transport
- Streamlined and not drift downstream
- Rugged and simple to construct
- Inexpensive

Various devices have been designed and used for monitoring purposes (Vanoni, 2006). Many share the basic characteristic of continuously capturing a sample of suspended sediment from the main flow of the river through principles of natural sedimentation (Cheng, 1997). However, the main development issue is ensuring a sampling device which operated isokinetically i.e. the velocity of the water entering and exiting the sampling device is consistent with the ambient conditions. Samplers which have been developed in the past (e.g. the IS^3) have been designed to capture a bulk sample of fine sediment for determining the geochemical and physical characteristics, with little consideration of the design's ability to operate isokinetically, or provide a representative sample of the transported material (Scrudato et al., 1988). There has also been a lack of experimental and field testing of their sampling efficiency, with little concern of the sampler's ability to trap a mass of sediment which is representative of the ambient flux.

The sampler designed by Phillips *et al.* (2000) was designed specifically to characterise the fluvial fine sediment flux. The Time Integrated Mass- flux sampler (TIMs) is anchored to the river bed using metal stakes (or similar), positioned with 4mm diameter inlet perpendicular to the direction of flow. Water passes through the inlet and into the expansion chamber. Here, the velocity of flow is reduced by a factor of 600 to encourage sedimentation of particles in transport. The water flows through the expansion chamber and out via the outlet. The apparatus is subject to the full range of flow conditions and sediment fluxes over the sampling period, providing a continuous record fine sediment flux, which will be representative of all events (Walling et al., 2008a).

The streamlined design (Figure 2.5) minimises flow intrusion, altering the flow magnitude by no more than 20% in addition to allowing the flow to exit unimpeded, thereby minimising sampling bias which is often inevitable using other methods (Fox and Papanicolaou, 2007). Although laboratory experiments have revealed that the trapped proportion is significantly coarser than the ambient particles, the occurrence of fine suspended sediment flocs in a natural environment is likely to enhance the sampling efficiency in field conditions (Woodward and Walling, 2007). Phillips *et al.* (2000) found this to be the case during field calibrations in which the particle size distribution captured by the TIMs were statistically representative of the ambient particle size distributions, which ranged from 1.6 – 5.3µm. However, in the context of this research, the particles present in the upland catchments of the Esk and Upper Derwent are believed to be coarser than the fine sediment (< 62.5µm) conditions for which the sampler has been designed for which should enhance the trapping efficiency in the sampler due to a reduced settling velocity threshold (Bracken and Warburton, 2005).

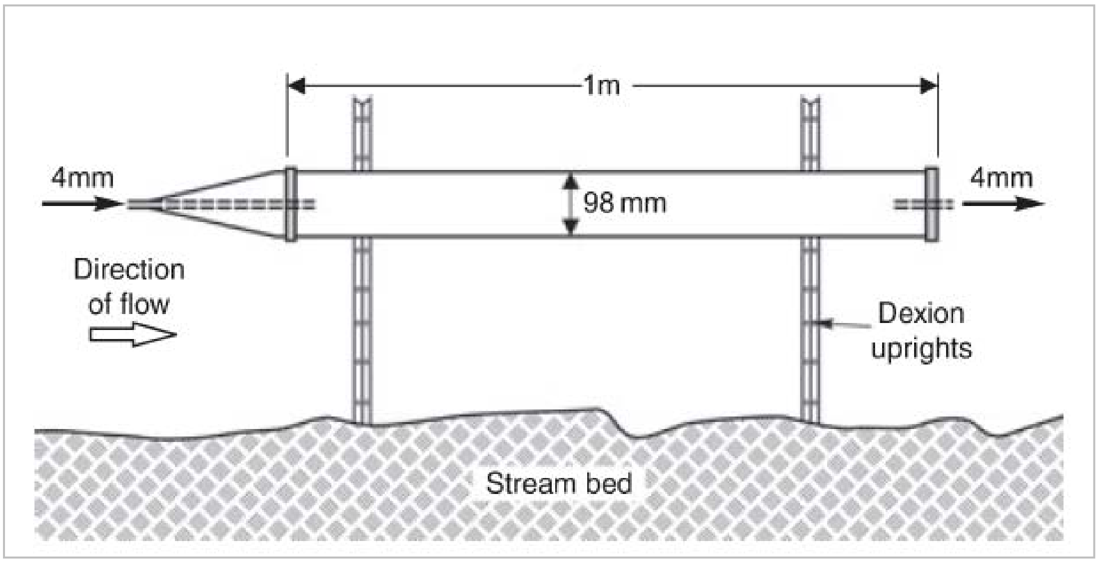

Figure 2.5: An example of a Time-Integrated Mass-flux Sampler (Fox and Papanicolaou, 2007).

Additional attempts to validate the TIMs as a representative means of collecting fine suspended sediment have been largely successful. Russell *et al.* (2001) found that the sampler provided a means of collecting a geochemically representative sample of the ambient fine suspended sediment. However, attempts by Phillips *et al.* (2000) to validate the sampling device as a means of collecting a mass of sediment which is representative of the ambient suspended sediment flux showed that the efficiency is dependent on the particle size of the sediment being transported. In lab tests, using a high proportion of very fine (< 2µm), chemically dispersed fine sediment with inflow velocities of between 0.3 and

0.6 m s^{-1}, the sampler retained between 31 and 71% of the inflowing sediment. The sampling efficiency decreases as the flow velocity increase and as the particles become finer.

Attempts to validate these samplers as a means of collecting a suspended sediment sample that is proportional to the actual suspended sediment load are limited in the literature. Hatfield & Maher (2008) found that two monitoring locations in the NW of England showed strong significant correlations between the trapped mass recovered from the TIMs and the maximum recorded discharge. The R^2 values for the bi-plots were 0.97 for the River Derwent and 0.89 for the smaller Newlands Beck, with significance levels > 95%. However, these data were collected over a limited monitoring period, with only 6 collections of the TIMs. Therefore, although this appears to show that the TIMs may be effective at trapping a proportionate mass of sediment relative to the ambient load, the significance of the results should be treated with some caution.

Additional validation work using the TIMs was conducted by McDonald *et al.* (2010). Considerable modifications were made to the device to make it suitable for the environmental conditions of the high Arctic. Specifically, the body length of the sampler was reduced from the standard 1000 mm to 228 mm, whilst the diameter of the body was also reduced from 100 mm to 63.5 mm. The diameter of the inlet was also reduced from the standard 4 mm to 2 mm. These modifications are likely to have generated an increased range of laminar flow in the inlet, reducing trap inflow by generating hydraulic discontinuity between stream and inlet flows (McDonald et al., 2010). Therefore, the sampling efficiency is likely to be undermined. Despite this, two variations in design were tested. The first was fixed at a known height above the bed, whereas the alternate sampler automatically adjusted its location within the vertical profile to ensure sampling at 60% of the depth.

Both traps showed weak linear relationships between actual and potential mass of sediment captured (R^2 = 0.434 fixed, R^2 = 0.429 variable, n = 23) with the difference between the actual and potential capture success varying from 20% to 150% (as demonstrated in Figure 2.4 (McDonald et al., 2010).

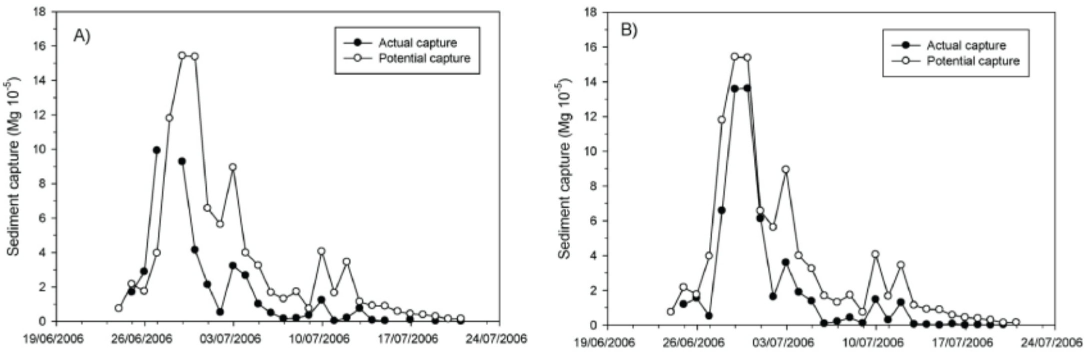

Figure 2.6: The sampling efficiency of the fixed model (A) and variable model traps (B) (McDonald *et al.* (2010))

The concerns which have been highlighted over the sampler's ability to capture a suspended sediment mass which is representative of the ambient flux can to an extent be explained by the changes made to the sampler. Specifically, the greater difference between potential and actual trapping at under low flow conditions could be a result of the laminar flow and subsequent hydraulic discontinuity at velocities below 1.1 m s^{-1}. Additionally, the smaller sampler body would reduce the residence time of the inflowing water, offering less chance for the entrained fine sediment to settle. The efficiency of the original TIMs design could therefore provide better estimates of ambient fine sediment flux than the modified designs offered by McDonald *et al.* (2010).

2.8.5 Flux estimates using turbidity measurements

2.8.5.1 Introduction

Turbidity is defined as the decrease in the transparency of a solution due to the presence of sediment particles, coloured organic matter and the water itself which causes incident light to be scattered, reflected and attenuated (Ziegler, 2002). It is the most widely used surrogate for measuring suspended sediment concentration (Gray and Gartner, 2009; Pruitt, 2003). Factors contributing to its popularity are:

- Fully functioning turbidity monitoring stations are relatively inexpensive to create (< £3,000) with relatively minimal operating and analytical costs (associated with calibration) following instrument installation (Wass and Leeks, 1999).
- Modern probes are reliable and not prone to failure or drift.
- They require minimal maintenance, especially with the use of mechanical wipers on self-cleaning probes.
- They are easy to operate and require minimal training.
- They cause minimal disruption to flow due to their size (Pratt and Parchure, 2002).
- They are ideal for research requiring high-frequency sampling, facilitating the capture of within-storm sediment dynamics and reliable load estimates. Turbidity probes have been shown to produce 50 times more data than a daily suspended sediment discharge gauging station (Schoellhamer and Wright, 2002).
- It is often possible to produce strong statistical relationships between turbidity and suspended sediment concentrations (Gippel, 1989; Gippel, 1995).
- Point measurements can be highly correlated to mean cross-sectional suspended sediment concentrations (Schoellhamer and Wright, 2002).
- When correctly calibrated, turbidity probes generally conform to the criteria set out by Gray *et al.* (2002) for their given operating range:

Range of suspended sediment concentrations (mg L^{-1})	Acceptable uncertainty %
0 – 10	50
10 – 100	25 – 50
100 – 1,000	25 – 15
> 1000	15

Table 2.4: Acceptable uncertainty in estimating SSCs as established by Gray *et al.* (2002).

2.8.5.2 Background Theory

Turbidity probes are designed to measure the optical properties of the water in one of two ways: turbidimeters (or transmissometers) operate by measuring the loss of intensity of a beam of light over a known path length using probe specific empirical calibration information (Wren, 2002), whereas nephlometric turbidity meters measure the degree to which a beam of light is scattered (Orwin et al., 2010). Nephelometric turbidity probes, by definition, measure the amount of side scattering of visible or infra-red light at an angle of 90° from the incident beam (Gray and Gartner, 2009). This is the most widely used configuration for the measurement of turbidity. However, variations in turbidity probe designs allow measurement using forward scattered (e.g. MoniTurb-F) and backscattered detection (e.g. Campbell Scientific OBS–3) at angles of 12° and 140-165° respectively. However, probes utilising scattering configurations deviating from 90° do not currently comply with international standard methods and therefore cannot be used for regulatory purposes (Anderson, 2004). This angle of detection is the critical factor in the design of turbidity probes (Davies-Colley and Smith, 2001). The range of probe configurations is shown in Figure 2.7.

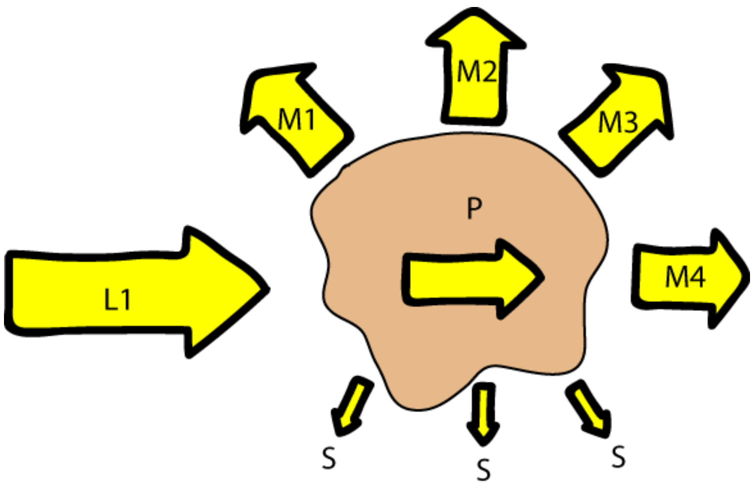

Figure 2.7: Diagram demonstrating the ways in which light is absorbed and reflected by materials within water and how this is may be measured by turbidity probes of varying design. Where: **P** = Sample; **L1** = Incident beam of light; **M1** = Backscatter detection method; **M2** = Scattered light beam at 90°; **M3** = Forward scatter detection method (12°) ; **M4** = Transmitted detection method ; **S** = Scattered Light.

2.6.5.3 Effects of internal Configurations

Transmissometers (as with all turbidimeters) are well suited for environments with relatively stable particle size distributions. These probes are very sensitive at low suspended sediment concentrations; however, the maximum operational conditions for this design may be as low as 50 mg L^{-1}, rendering their use solely for very low turbidity environments (e.g. drinking water quality assessment). Probes measuring the amount of scattering at 90° are best suited to relatively low level monitoring with a typical operating range of 0 – 1000 mg L^{-1}, providing accurate measurements with associated error of approx. 0.5 NTU. This configuration is also less sensitive to variations in particle size (Sadar, 1998). Conversely, optical backscatterance (OBS) is suited for use in high-turbidity environments with an operational range of 0 – 5 g L^{-1} for silt and clay samples, which may be extended upwards of 50 g L^{-1} for sand samples with associated errors in the order of 1 mg L^{-1} (or 1%)

for silts and clays and 0.5 g L^{-1} (or 1%) for sand samples (D & A Instrument Company, 2010). This is a much larger signal range than is afforded by side-scattering turbidity probes although its lack of precision is likely to lead to significant errors at low suspended sediment concentrations. The OBS systems are also highly sensitive to particle size distributions (Kineke and Sternberg, 1992; Ludwig and Hanes, 1990) and are developed for optimal operation with particles ranging between 200 – 400 µm in diameter (Black and Rosenberg, 1994), a criterion which is often not met in river systems. Despite these limitations, OBS probes do have a reduced sensitivity to bubbles (Kineke and Sternberg, 1992) and represent particle size more effectively (Orwin et al., 2010). Finally; a combination of multiple beam light sources can be utilised. Configurations often have a light sensor at 90° to the incident beam and additional detectors at other angles. A ratio algorithm is utilised to produce a turbidity measurement from a combination of the detector readings.

The wavelength of the incident beam is also an important factor in the amount of light that is scattered. Probes utilising incident beams with wavelengths within the white light spectrum e.g. 400 – 600 nm (as specified by USEPA Method 180.1 (United States Environmental Protection Agency, 1993) are more susceptible to the impacts of naturally occurring colour within the water (i.e. dissolved material or coloured particles) when the wavelengths overlap the absorptive spectra within the sample matrix. This results in a negative bias (Sadar, 2002), whereas turbidity probes utilising light with wavelengths of 860 – 890nm are relatively insensitive to the effects of colour in the water (Ankcorn, 2003; Pavelich, 2002). It is also important to note that small particles more effectively scatter light with short wavelengths, whereas larger particles scatter light with long wavelengths most efficiently (Sadar, 2002).

The path length of the scattered light is a design parameter which affects both instrument sensitivity and linearity. Sensitivity increases as path length increases, but linearity is sacrificed at high particle concentrations due to multiple scattering and absorbance. Conversely, if the path length is decreased, the linearity range is increased but sensitivity is lost at low concentrations although, this trade-off can be eliminated with an adjustable path length (Sadar, 1998). Ambient light interference also has the potential to interfere with the turbidity measurement, with increases in stray light causing a positive bias i.e. higher than expected turbidity measurements (Sadar, 2002).

2.6.5.4 External Effects

Variability in turbidity measured in rivers is largely controlled by SSCs. Teixeira & Caliari (2005) found that 72% of the changes in turbidity could be accounted for by simultaneous changes in suspended sediment concentrations. However, since turbidity is only a relative measure of side scattering of light with reference to an arbitrary standard (in this case Formazin) (Davies-Colley and Smith, 2001), variations in the environmental conditions the probe is operating in has the potential to have significant effects on the scattering of light and therefore the turbidity measured. This section describes some of these environmental factors and discusses laboratory and field experiments to account for the variability in the system in order to produce accurate estimates of suspended sediment concentrations from in-stream turbidity measurements.

Despite the adoption of a probe which is believed to be relatively insensitive to the colour of sediment due to the near infra-red light source, Sutherland *et al.* (2000) found the output value of a probe using near infra-red light was highly dependent on the level of blackness (Munsell value) of sediment, with small turbidity responses for black sediments and the greatest response from white sediments. Although the colour of the natural fluvial sediments do not vary as much as the artificial sediment colourings used by Sutherland *et al.* (2000), there may be some tendency for turbidity measurements to vary between locations due to this effect.

In addition to suspended sediment, other suspended substances such as diatoms, algae, and organic detritus cause turbidity in the water column (Pratt and Parchure, 2002). Turbidity probes are not able to distinguish these materials from suspended sediment. Therefore, if organic matter concentrations are high, turbidity may not provide an accurate measurement of suspended sediment concentrations. Conversely, it has been found that organic-rich samples may strongly absorb the incident light, thereby reducing the amount of light which is able to reach the sensor, producing artificially low turbidity readings (Sadar, 2002). It is therefore suggested that sediment samples are tested for organic content using the standard ignition method (Heiri *et al.* (2001)).

The size of particles in a sample is a major factor affecting the turbidity (Kineke and Sternberg, 1992), with probes providing vastly different turbidity measurements for identical concentrations of clay and sand samples. These variations can be up to a factor of 10 (D & A Instrument Company, 2010). This is due to the attenuation of light by particles (through reflection and refraction) being dependent not on the number of fine sediment particles, but the inverse of the geometric cross-section per unit volume for inorganic materials larger than 1.2µm (Davies-Colley and Smith, 2001).

Sensor fouling caused by biological growth or scratches may also impinge in the quality of turbidity measurements (Anderson, 2004), resulting in spurious results. When the interference is over a limited time, removal and interpolation may be possible, although extended periods of missing data may be unsalvageable through this method, resulting in gaps in the time-series unless alternative correction methods are adopted e.g. infilling using a well constrained sediment rating curve.

Assuming that that a turbidity probe is selected with the correct internal configuration for the operating environment, the external effects of the operating environment can are often minimal providing that turbidity – suspended sediment concentrations are collected across a range of flow magnitudes and at various times of the year, resulting in a high degree of accuracy in SSC estimates.

2.8.6 Other Surrogates

Although this section has focussed on the available turbidity methods of measuring suspended sediment concentrations, other methods are available for the indirect assessment of SSCs, although less widely used in fluvial studies. These include acoustic, nuclear and Laser in situ scattering and transmissometry (LISST) technologies. A description of the operating principles and inherent advantages and disadvantages are provided in Table 2.5. Each method described varies appreciably from turbidity probes, and each technology has specific issues making their deployment potentially more problematic and arguably no more accurate that the use of a well calibrated turbidity probe in fluvial upland environment.

Technology	Operating Principle	Advantages	Disadvantages	References
Acoustic (Acoustic Doppler Velocitymeters (ADV) and Acoustic Doppler Current Profiler (ADCP) systems)	High frequency sound directed at measurement sample. Acoustic attenuation is used to measure suspended-silt and clay concentration, acoustic backscatter is used to measure the concentration of suspended sand	None invasive measurement Measures over vertical range High temporal resolution Operating range between 10 – 20,000 mg L^{-1} for silt and clay concentrations and 10 – 3,000 mg L^{-1} for sand concentrations Errors of less than 10%	Backscattered strength dependant on particle size as well as concentration Calibration must be done using water and materials of the natural system Signal attenuation at high particle concentration	Wren *et al.* (2000) Schindl *et al.* (2005) Topping *et al.*(2007) Chanson *et al.*(2008) Tessier *et al.* (2008)
Laser in situ scattering and transmissometry (LISST)	The attenuation intensity of the laser transmitted through a sample is measured. The change between the transmitted and received intensity can be converted to a beam attenuation coefficient providing a measure of water clarity. Determination can also be achieved through Nephelometry.	Measurements are theoretically not sensitive to the grain size distribution Nephelometric probes have an operational range of 0 – 5000 mNTU whilst being sensitive at low levels - Reported error of 5%	Studies using attenuation probes show low explained variance (R^2 of 0.23 - 0.44) Expensive Flow intrusive	Wren *et al.* (2000) Fugate & Friedrichs (2002) Sadar (2004)
Nuclear	Sediment concentrations can be measured through the backscattering or transmission of radiation from an artificial source or by measuring the radiation emitted naturally by sediments	Low power consumption, wide particle size and concentration measuring range (500 – 100,000 mg L^{-1}) Insensitive to water colour and organic content Automated system Linear response	Field calibration is difficult Suited to sediment concentrations exceeding 1,000 mg L^{-1} Subject to decay Not applicable for shallow (depth < 1.5m) streams Sensitive to changes in temperature	Tazioli (1980) Berke & Rakoczi (1981) Wren *et al.* (2000)

Table 2.5: Summary of available indirect means of assessing suspended sediment concentrations in river environments

2.9 Chapter Summary

Upland rivers represent some of the most dramatic and dynamic fluvial environments of the UK. They are also some of the most responsive to external forcing (e.g. climate). Much of the research conducted in these environments has focused on the direct response of these catchments to specific pressures (such as deforestation) in very small catchments. Little work has been conducted on assessing the larger-scale fine-sediment dynamics in catchments > $10km^2$, including the variability in material properties and transfer rates across these catchments. The fine sediment dynamics in these catchments also vary at the event to annual time-scales. Assessment of this variability can provide valuable information on the sediment delivery system and is a novel approach to assessing the provenance of sediment delivered to the river.

A comprehensive range of the methods commonly adopted for the determination of fluvial suspended sediment transfer rates is also presented. These methods include direct and indirect techniques and a discussion of appropriate sampling frameworks. Advantages, limitations and examples of application are provided throughout.

Chapter 3: Characteristics of the Research Area and Catchments

3.1 Overview

This chapter provides background information to the geographical characteristics of the research area and monitored catchments.

3.2 Landscape Evolution

Two adjacent catchments were chosen for this research project, the Esk and Upper Derwent catchments. Both are based in the region of North Yorkshire in the United Kingdom.

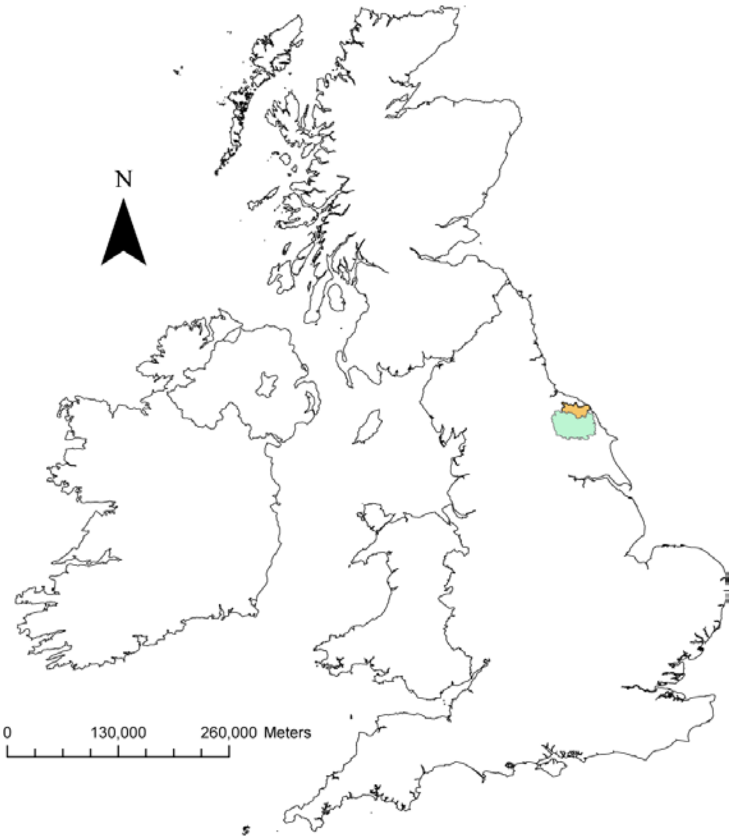

Figure 3.1: Illustration of the studied region. The Esk catchment is shaded in orange and the Upper Derwent catchment in green.

This area has been heavily modified following the most recent glaciations which ended approximately 20,000 years ago. However, it is believed this ice did not extend over the hills. Ice pushed inland from the north or north-east up Eskdale to Lealholm and up the Murk Esk. As the climate warmed, the ice fields on the moors began to melt (Carroll and Bendelow, 1981). The resulting meltwater was unable to escape eastwards, westward or northwards because it was blocked by ice. This meant huge torrents of water were forced south from the Esk valley, gouging out the deep Newtondale valley (in the NYMNP north of Pickering) as it went. In the area of the Vale of Pickering, water from the moors formed a vast lake. After a while this lake filled its basin and then overflowed at the lowest point which was at Kirkham. Here it cut the steep sided Kirkham gorge. When the glacier finally retreated they left deep deposits of boulder clay and glacial alluvium behind (Spratt and Harrison, 1989).

3.3 Esk Catchment Drainage, Topography and Habitat

The headwaters of the River Esk originate as a group of moor-edge springs at Esklets on Westerdale Moor in the North York Moors National Park at an altitude of 432 m above sea level (North York Moors National Park Authority, 2001). Other headwater tributaries include Tower Beck and Hob Hole, which drain the upland hills to the south and Commondale Beck which drains the relatively low lying area to the North (Figure 3.2). From the headwaters, the Esk traverses the landscape for 42 km from West to East, connecting with the major tributaries of Danby Beck, Great Fryup Beck, Stonegate Beck, Glaisdale Beck, Butter Beck and finally the Murk Esk draining an area of 362 km^2 before joining the North Sea at Whitby (Figure 3.2). The details of the major sub-catchments of the River Esk can be seen in Table 3.1.

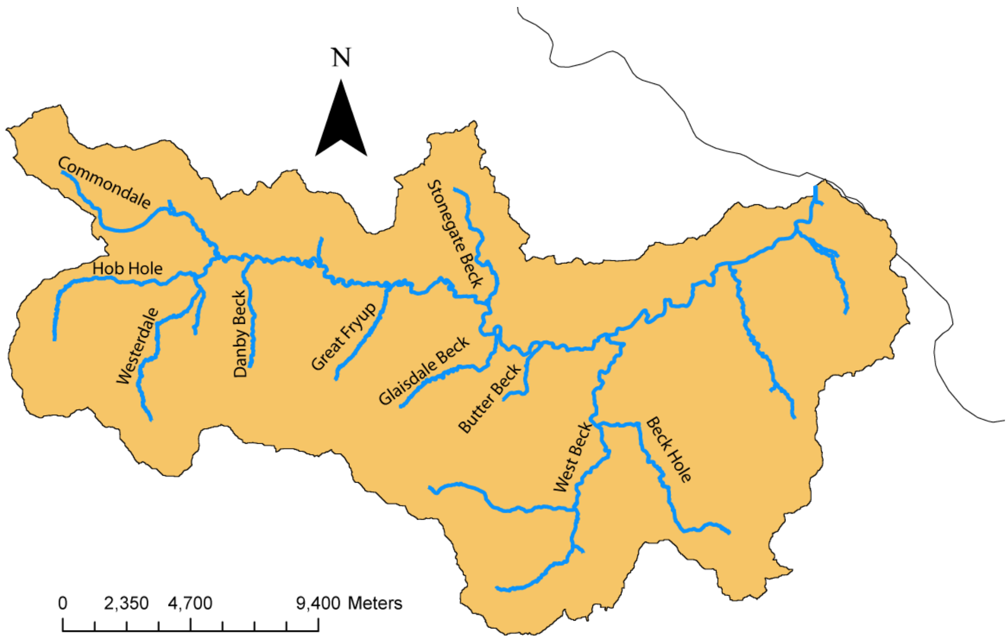

Figure 3.2: Background map of the Esk catchment, highlighting the major tributaries

	Catchment Area (km^2)	Channel Length (km)	Joins the Esk *x* km downstream of Esklets on Westerdale moor
Tower Beck	6.77	2.33	9.49
Baysdale Beck	20.28	10.14	10.30
Commondale Beck	24.18	10.42	11.51
Danby Beck	12.51	5.18	13.50
Great Fryup Beck	14.33	5.97	22.77
Stonegate Beck	16.62	6.59	26.24
Glaisdale at Esk	15.56	6.99	32.01
Butter Beck	9.13	3.32	34.52
West Beck	90.67	15.81	38.20
Beck Hole	29.74	15.00	38.20

Table 3.1: Morphometric features of the Esk sub-catchments

The vast majority of the River Esk is constrained by steep valley sides with narrow floodplains which develop to a maximum width of 300 m at Whitby. The floodplains offer a limited storage capacity, especially in the headwaters.

The Esk is a river of both ecological and economical important importance at a national scale. It is the only river in Yorkshire to support salmon and sea trout (Evans et al., 2005) and is one of only two rivers on the East coast of England to have known populations of Pearl Mussels (Geist, 2005). Furthermore, the Esk supports four other species (the otter, water vole, kingfisher and dipper) which are listed as threatened or declining in the UK Biodiversity Action Plan (North York Moors National Park Authority, 2001). The rivers importance is recognised by the assignment of one Special Protection Area (SPA) in the upper Esk and a further 17 Sites of Special Scientific Interest (SSSI). A total of 237km of the river Esk (and tributaries) are protected under the EC Freshwater Fish Directive (Environment Agency, 2006).

3.4 Upper Derwent Drainage, Topography and Habitat

The Yorkshire Derwent catchment spans 2048 km^2 and includes the River Derwent, River Rye, Sea Cut, River Hertford, Costa Beck, Bielby Beck, and Pocklington Canal. The headwaters of the Derwent are the Vales of Pickering, Yorkshire Wolds and North York Moors before joining the River Derwent which joins the River Ouse at a tidal barrage at Barmby (Environment Agency, 2007; Joint Nature Conservation Committee, 2006). This research focuses on the Rye sub-catchment of the River Derwent. The headwaters of which include Blow Gill, Wheat Beck and Low Gill. These rise in the upland area of the Southern section of the NYMNP (North York Moor National Park), at an altitude of 370m (Figure 3.3). The development of floodplains downstream of Helmsley demonstrates the movement to a lowland area (Figure 3.3). The area of interest in the Upper Derwent catchment spans from the headwaters draining the NYMNP, down the River Rye and contributing tributaries as far as West Ness along the main Rye River (Figure 3.3). This gauged catchment spans an area of 236km^2. The morphometric characteristics of each of the sub-catchments within the Rye catchment can be seen in Table 3.2:

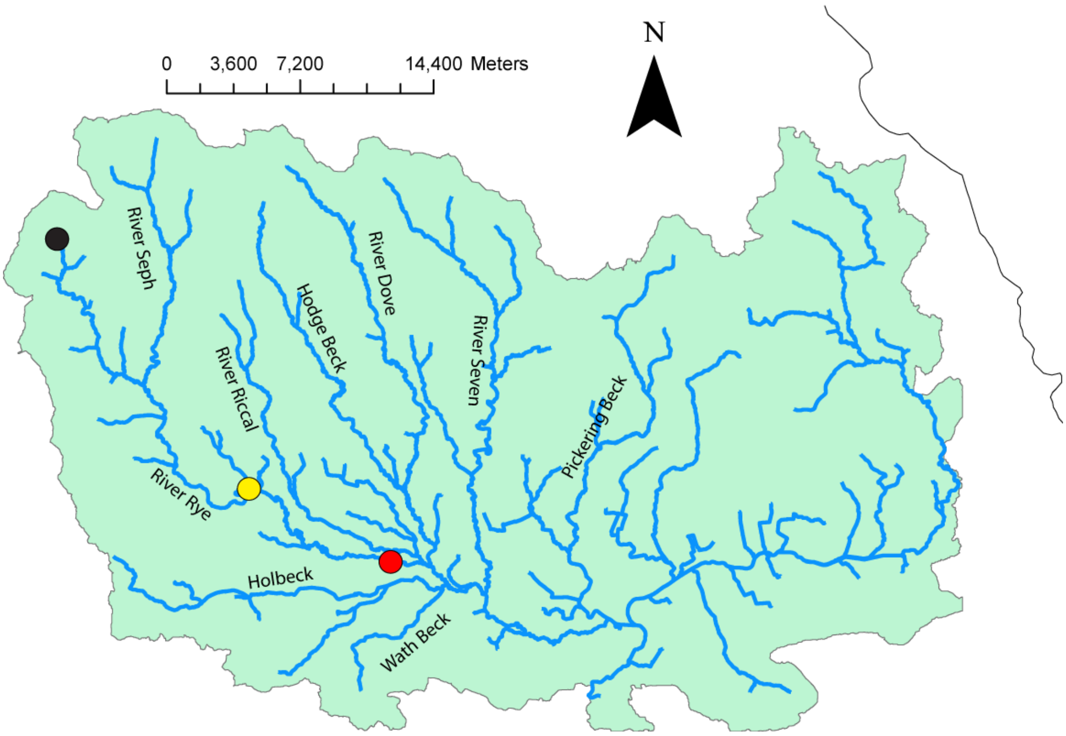

Figure 3.3: Background map of the Upper Derwent catchment highlighting major tributaries. The black circle represents the headwaters, Yellow circle the River Rye at Helmsley and the red circle the River Rye at West Ness.

Sub-catchment	Catchment Area (km^2)	Channel Length (km)	Joins Rye at *x* km downstream of source:
Arns Gill	5.74	1.58	2.57
Wheat Beck	5.90	1.14	3.88
Blow Gill	4.80	0.66	7.35
Leadhill Beck	7.96	3.63	13.97
River Seph	67.99	20.68	15.74
Deep Gill	10.59	4.35	18.91
Low Gill	21.67	2.47	23.13
Etton Gill	14.48	4.42	32.02
River Riccall	44.48	27.10	51.39
Holbeck	90.10	23.37	54.58
Wath Beck	26.96	10.93	54.58
Hodge Beck	50.10	23.19	52.28
River Dove	131.58	39.96	52.28
River Seven	121.87	39.61	58.00
Slingsby Carr Cut	5.50	0.74	58.95
Red Bridge Sewer	16.72	3.77	32.11
Pickering Beck	70.11	27.27	68.94
Costa Beck	136.48	16.49	68.94

Table 3.2: Morphometric features of the Upper Derwent sub-catchments

3.5 Geology

The geology of the North York Moors is dominated by Limestones, sandstones and shales of the Jurassic Period. Compared to other upland areas of the UK these are some of the youngest and softest rocks. The bedrock stratigraphy consists of shales and ironstones being the oldest, followed by Ravenscar sandstones, Oxford clay and finally Corallian Limestone. These rocks were uplifted and tilted Southwards by the earth's movements, resulting in the exposure of the oldest bands of shales and ironstone on the northern scarp. The middle layers consist of sandstones where moorland dominates (Figure 3.4 and 3.5). Immediately south of moorland, a thin belt of Oxford clay is present where grassland is sustained. The youngest layers, limestones, are present on the southern fringe which produces a dramatically steep and unstable scarp due to the presence of underlying softer rocks (Figure 3.5). South of this limestone scarp are the Tabular Hills which roll gently southwards as far as Pickering. This area consists of alternating layers of calcareous grit and limestone which produces variations in soil fertility (Figure 3.5). At the foot of these hills, Oxford clay dominates from East to West (Spratt and Harrison, 1989).

The bedrock geology of the Esk catchment was formed in the mid Jurassic (176 – 161 Ma BP) and the lower Jurassic periods (200 – 176 Ma BP). The Esk catchment is dominated by a combination of Sandstone, Siltstone and mudstone, which accounts for 64% of the entire catchment area. However, between sub-catchments of the Esk there is variability in the geological units present. The percentage of sandstone, siltstone and mudstone varies between 77% (in the Hob Hole catchment) and 30% (in the Tower Beck catchment).

The bedrock geology of the Upper Derwent is dominated by mudstone which accounts for 34% of the entire catchment area. These Ampthill Clay and Kimmeridge Clay formations were formed in the late Jurassic (159 – 147 Ma BP). Late Jurassic Sandstone also accounts for 25% of the catchment's geology.

3.6 Climate

The area in and around the NYMNP may be characterised as a cold and wet temperate climate with temperatures during winter typically between -1 to 7 °C and between 11 and 22°C during the summer. At Westerdale in 2009, 228 days had a maximum temperature greater than 10°C and three ice days (where the temperature remained below zero all day) were recorded (http://weather.westerdale.info). The vast majority of the precipitation in the North York Moors is received as rainfall with over 130 rain days (i.e. > 0.2mm rainfall) per annum, with an additional 20 snow fall days on average. At Westerdale in 2009, 130 days recorded over 0.2 mm of rainfall whereas only six days had over 25 mm of snowfall (http://weather.westerdale.info). The distribution of rainfall in this region is complicated by local orographic effects with average annual rainfall at Moorhouse in the Northern Pennines is 1930 mm yr^{-1}, whereas only the highest points in the NYMNP receive on average over 1000 mm yr^{-1} (Simmons, 2003). In 2009, Westerdale received just 820 mm of rainfall (http://weather.westerdale.info).

Figure 3.4: Bedrock geology map of the Esk catchment

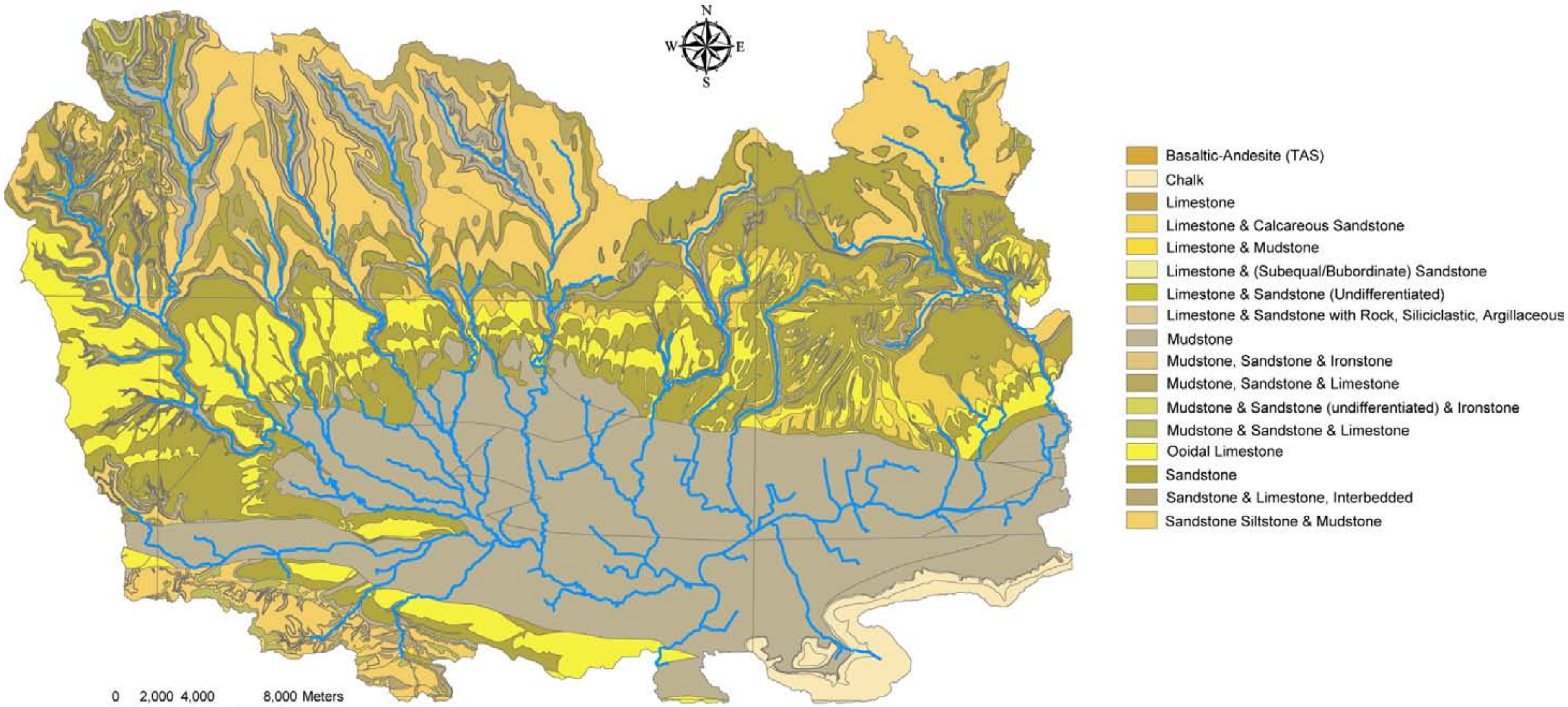

Figure 3.5: Bedrock geology map of the Upper Derwent catchment

3.7 Soils

The great variety of soils across the two catchments and the general absence of glacial deposits explain the importance of solid rocks in the formation of the soils (Carroll and Bendelow, 1981). The principal soil cover of the North York Moors is a clayey stagnohumic gley over shale or mudstone (26% by area). Heather nearly always dominates on this soil group. On the steepest slopes, a coarse loamy brown earth can be found (9% by area). Brown earths or stagnopodzols over sandstone or grit are widespread on the gentle Hambilton, Tabular and Hackness Hills (south of the moorland hills) (5% by area). Raw peat also covers 50km^2 (5% by area). This forms on the moderate and gentle moorland slopes.

3.8 Land Use

The land use in the Esk catchment is dominated by dwarf shrub heath (33%), along with improved grassland (18%). 12% of the catchment is also used for horticulture. However, the area utilised for cereals is limited (< 1%).

There is considerable variability in the land use found in the upper reaches of the Esk catchment, which is drained by Commondale Beck, Tower Beck and Westerdale, and Hob Hole. In these catchments, there is almost no cereal production. Interestingly, there is a contrast in the amount of land populated by shrub heath between the tributaries draining from West to East and those flowing from SW to East with shrubbery in the Western catchments (Commondale and Hob Hole) each accounting for 60% of the land use whereas in the catchments of Tower Beck and Westerdale, this figure drops to 26% and 30% respectively, which is below the catchment wide average. In Westerdale, rather than shrub, there is a significant amount of bog (30%), classified as a result of peat depth greater than 0.5 m. In Tower Beck catchment, there is a significant amount of improved grassland (29%).

Moving down the main Esk, between 6 Arch Bridge and the confluence between West Beck and the Esk, the percentage of land used for coniferous plantation and cereals, stays fairly constant with variations under 1%, as does the amount of rough grass and acid grass (with slight reductions from 6% to 4% and 3% to 2% respectively). However, the amount of improved grassland does increase (from 13% to 22% respectively). The downstream increases in improved grassland are a consequence of relatively high percentages in all of the sub-catchments downstream of 6 Arch Bridge. Downstream of 6 Arch Bridge, there is also a general decline in the proportion of the catchment which is dominated by shrub (from 41% to 35%). This is due to the headwater catchments having much greater percentage cover of this crop than the lower reaches (except for Beck Hole).

Downstream of Egton Bridge, the Murk Esk joins the main River Esk. This large catchment is dominated by shrub, which accounts for 74% of the land use at Beck Hole and 41% at West Beck. Cereals and improved grassland are rare, combined accounting for only 6% and 4% of the catchment areas respectively. Unlike the other sub-catchments of the Esk, coniferous forestry accounts for a significant proportion of the land use (18%) in the West Beck catchment.

Generally, the Esk catchment is sparsely populated with isolated settlements in Westerdale (population of 175), Castleton, Danby (population of 1515), Lealholm & Glaisdale (population of 974) and Grosmont.(population of 335)

The land use in the Upper Derwent catchment is dominated by horticulture (26%) and improved grassland (16%). Although cereals (11%), broad leafed woodland (8%), coniferous woodland (9%), dwarf shrub (9%) and open shrub (3%) are also evident throughout the catchment. This catchment is sparsely populated, with suburban/urban land accounting for only 2% of the catchment. The population of the Ryedale area as of 2001 was 50,872. The settlements contributing to this total area Helmsley (population of 3240), Kirkbymoorside (population of 3480), Malton (population of 5050), Norton East (population of 3680), Norton West (population of 3540), Pickering East (population of 3420) and Pickering West (population of 3740).

The Upper Derwent is an area with contrasting land uses between the upland and lowland area. This distribution is also influenced by the underlying geology present and therefore the soil depth and characteristics found within the area. In the Upper reaches, the catchments draining the North York Moors, the dominant geology is that of deltaic sandstone and mudstone which is responsible for the development of poor quality, acidic, peaty soils which provide limited opportunities for agriculture. As such, the upper tributaries are dominated by shrub heath, dwarf heath and bracken with isolated areas of improved grassland. For example, shrub accounts for 59%, 66%, 69% and 87% of the land use in the sub-catchments of Arns Gill, Blow Gill, Wheat Beck and Rye at Headwaters respectively. Improved grassland in each of these headwater sub-catchments is below 6%. The River Seph is also a headwater catchment of the Rye River. However, this catchment's land use is somewhat different; only 28% of this area is covered by shrub, with 22% of the catchment being used for improved grassland. Further down the River Rye, moving out of the upland area, there is much more diversity in the range of land uses within the sub-catchments. The sub-catchments of Low Gill, Wath Beck, Holbeck and Costa Beck are widely utilised for cereal production and horticulture, combined accounting for ~40% of the total land use in each of these catchments. Improved grassland also dominates in these lowland areas, with all of the contributing areas of the Rye below Church Bridge containing at least 15% improved grassland. However, the percentage of rough grazing stays fairly consistent throughout the catchment.

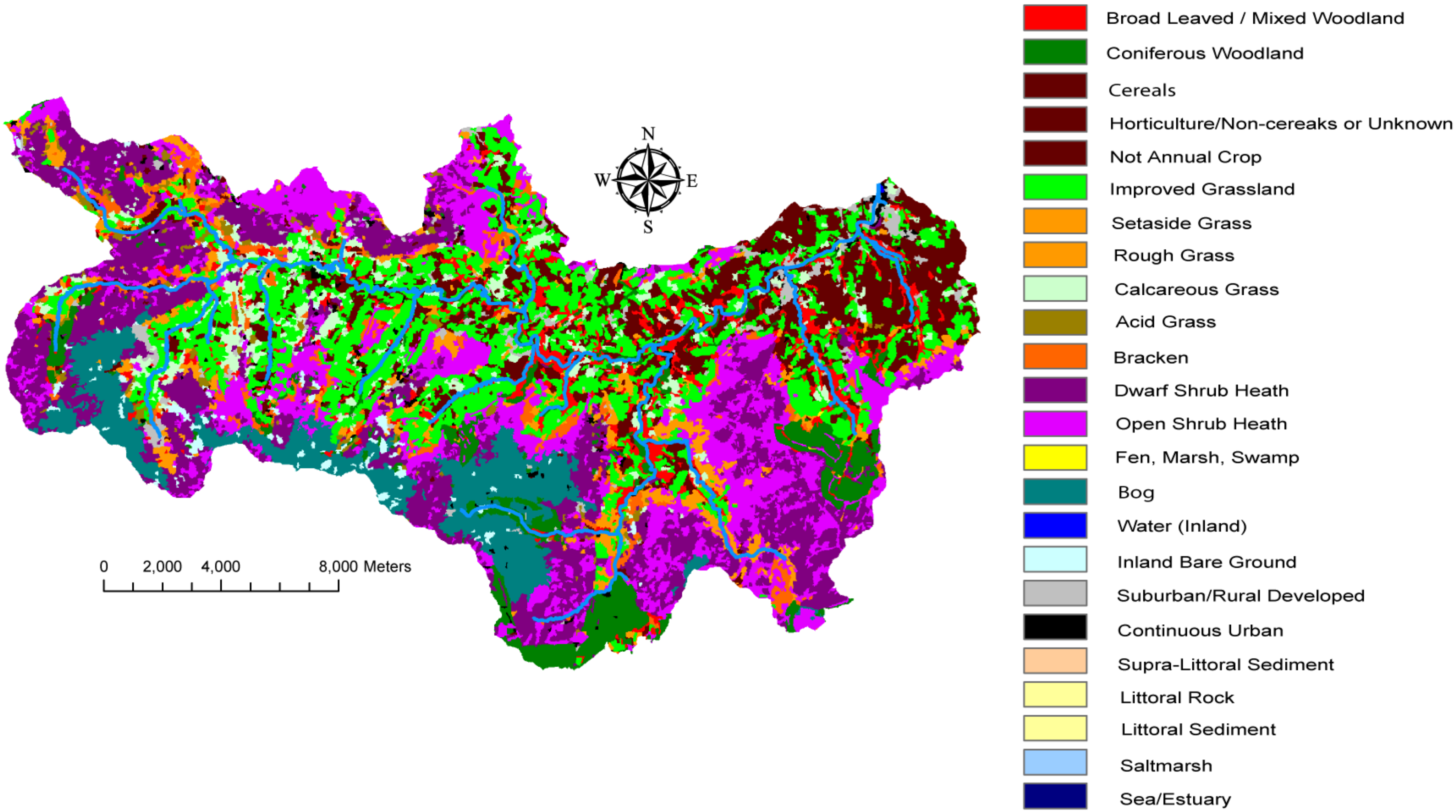

Figure 3.6: Land use map of the Esk catchment, distinguished by their broad habitat. Source: Land Cover Map 2000

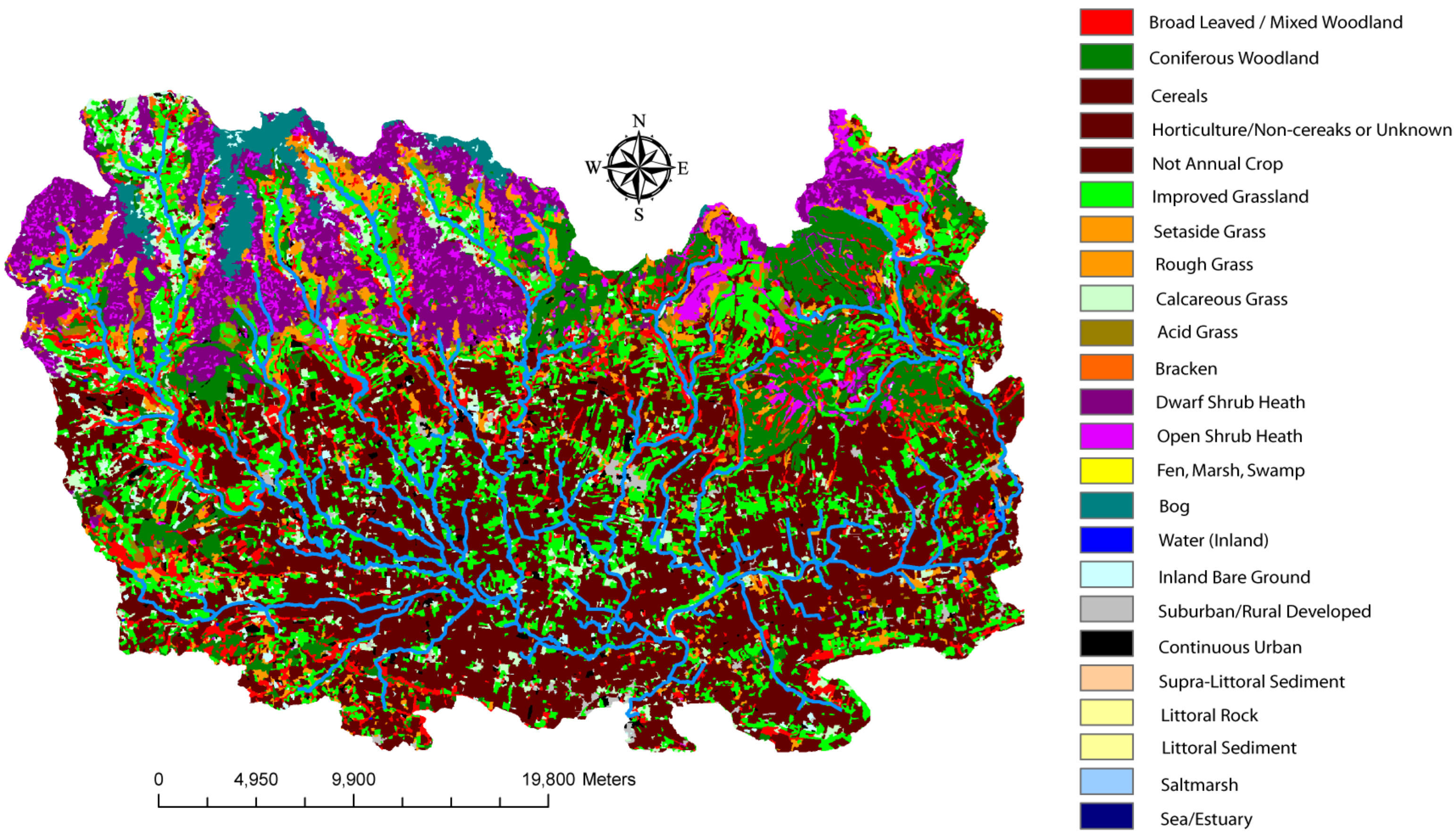

Figure 3.7: Land use map of the Upper Derwent catchment, distinguished by their broad habitat. Source: Land Cover Map 2000

3.5 Catchment Hydrology

The Esk catchment is currently gauged at the lower end of the catchment at Briggswath (NRFA Station ID: 27206), which has a catchment area of 325.25 km^2. This 30m wide multi-path ultrasonic gauging station was installed in 1992 and replaced the previous station at Sleights in 1998 (NRFA Station ID: 27050). The monitoring station at Sleights was a 25m wide, broad-crested masonry weir with a contributing area of 308 km^2 which operated from 1977. However, significant un-gauged floodplain flow rendered readings at high flows inaccurate. The overlap of six years between the gauging sites provides a sufficiently long period for cross-correlation ($R^2 = 0.98$, $P < 0.001$) and the generation of a synthetic record. This allows analysis of the long-term flow record to be conducted.

This combined data series spans from 1 October 1977 to 30 September 2009. However, due to issues with flow measurements for a significant period from 1 October 2001 to 30 September 2002; this year has been omitted from analysis. Over this period, the mean river flow is 5.57 $m^3 s^{-1}$, the median flow is 3.08 $m^3 s^{-1}$, with a flow range of 225.85 $m^3 s^{-1}$ and coefficient of variation (CV) of 166.63 % (Table 3.3). The three hydrological years with the highest average flow were 2000/01 (8.04 $m^3 s^{-1}$), 1978/79 (7.92 $m^3 s^{-1}$) and 1985-86 (7.71 $m^3 s^{-1}$).

The monitoring period of this research spanned the hydrological years of 2007/08 and 2008/09. In order to determine whether the flow conditions during this period are comparable with the preceding annual flow records, a Mann Whitney-U Test has been conducted. The median flow between September 1977 and October 2007 is 3.12 $m^3 s^{-1}$; whereas the median river flow for the 2007/08 and 2008/09 hydrological years are 2.96 and 2.02 $m^3 s^{-1}$ respectively which are both significantly different ($P < 0.05$) from the long term median annual flow record (Table 3.3).

	Median (m^3 s^{-1})	Min (m^3 s^{-1})	Max (m^3 s^{-1})	U	Z	*P*
1977 – 2007	3.12	0.01	225.86			
2007/08 (*n* = 35136)	2.96	0.03	151.34	1.8049e+10	2.4966	0.0063
2008/09 (*n* = 35040)	2.02	0.21	140.02	1.4069e+10	71.5840	< 0.001

Table 3.3: Summary statistics of measured flow at the Sleights and Briggswath gauging stations on the River Esk between 1977 and 2009 along with results of Mann Whitney-U Test between monitored years and long-term record

In the Upper Derwent catchment, there are several gauging stations which have a long river flow record. These are the gauging sites at Broadway Foot (NRFA Station ID: 27055), Kirkby Mills (NRFA Station ID 27042), Pickering (NRFA Station ID: 27057), Ness (NRFA Station ID: 27049) and Gatehouses (NRFA Station ID: 27038). In this chapter, analysis is limited to the Broadway Foot gauging station since this is in closest proximity to the headwaters of main Rye River where the main sediment monitoring is being undertaken.

The data from the Broadway Foot gauging station spans from October 1977 – September 2009. Between 1977 and 2007, the mean river flow is 2.25 m^3 s^{-1}, the median flow is 1.41 m^3 s^{-1}, with a flow range of 140.65 m^3 s^{-1} (Table 3.4). The three hydrological years with the highest average flow were 2000/01 (3.70 m^3 s^{-1}), 1978/79 (3.14 m^3 s^{-1}), and 1998/99 (3.01 m^3 s^{-1}). In order to determine whether the flow conditions over the period of this research are comparable with the preceding annual flow records, a Mann Whitney-U Test has been applied. The median flow for the 2007/08 and 2008/09 hydrological years is 1.65 and 1.41 m^3 s^{-1} respectively (Table 3.4). These are both statistically different from the long term median flow (P < 0.001) despite the median values of the long-term and 2008/09 hydrological records being identical. This is due to the Mann Whitney-U Test ranking all the values, and then comparing the mean ranks. In instances where the mean of the ranks of one group is lower than the mean of the ranks of the second group, a low *P* value would be produced, even though the medians of the two groups are identical (Hart, 2001).

	Median ($m^3 s^{-1}$)	Min ($m^3 s^{-1}$)	Max ($m^3 s^{-1}$)	U	Z	*P*
1977 – 2007	1.41	0.35	141.00			
2007/08 (*n* = 35136)	1.65	0.47	45.66	1.8438e+10	48.1486	< 0.001
2008/09 (*n* = 35040)	1.41	0.49	55.00	1.7073e+10	21.9135	< 0.001

Table 3.4: Summary statistics of measured flow at the Broadway Foot gauging station on the River Rye between 1977 and 2009 along with results of Mann Whitney-U Test between monitored years and long-term record

3.10 Catchment Management

The most significant driver of management and maintenance of the Esk and Upper Derwent catchments is the North York Moors National Park. This area spanning 1436 km^2 is the 4th largest National Park in the England and was designated a National Park in November 1952. In this designated area, there is 500 km^2 of open moorland and over 300 km^2 of woodland and arable farming with a population of approximately 25000 and visitor numbers exceeding 13m per year (Arnold-Forster, 2002).

Of this area, 352 km^2 is drained by the Esk catchment and 726 km^2 is drained by the Upper Derwent. Given that the a significant proportion of the Esk and Upper Derwent catchments are located within the North York Moors National Park, the authority has great potential to directly modify the landscape through their government allocated budget of £3 million and indirectly through encouraging sustainable land use through advice and training programmes. The main achievements of the NYMNP are; i) the encouragement of good environmental practice and sustainable management of the moorland to enhance moorland habitat and biodiversity; ii) the spraying of 6000 ha of invasive bracken on moorland and; iii) burning of 9400 ha of heather (Arnold-Forster, 2002). Further to these landscape changes, specific attempts have been made to directly improve the quality of the watercourses in both the Esk and Upper Derwent catchments.

In the Esk catchment, the main emphasis is on trying to return the river habitat to the conditions desirable for the endemic populations of Atlantic Salmon and Pearl Mussel. Much of this work was carried out under the guise of the River Esk Regeneration Programme between 1997 and 2001. During this period there was management of 21 km of riverbank, 9 km of river channel habitat improvements, stocking of 130 000 native Esk salmon fry, enhanced monitoring of fish and otter populations and the instalment of a fish weir at the gauging station at Sleights. Following the lapse of this project, subsequent management strategies have been adopted, namely through the River Esk Pearl Mussel and Salmon Recovery Project (EPMSRP). In the Esk catchment, regulatory options are not currently available for adoption. For example, the Catchment Sensitive Farming scheme which has been widely utilised through the UK is not currently in operation in the Esk Valley, nor is the catchment in a Nitrate Vulnerable Zone (NVZ). There is therefore little scope for direct intervention of farmer’s land use practices from the Environment Agency.

In the Upper Derwent catchment, many of the recent improvements to the watercourse have been achieved through the Upper Derwent Enhancement Project which ran from September 1998 to September 2001. Given that the Upper Derwent contains a nature reserve and a large area of SAC status land, much of the focus was geared towards beneficial improvements to Biodiversity Action Plan species such as the White-clawed crayfish, water-vole, otter, brown trout, grayling, bullhead, brook lamprey, kingfisher and dipper. In order to achieve this, 0.76 km of riverbank was stabilised and 4.93 km of bank-side stock was protected, with a total of 6.33 km of in-stream, riverbanks and land protected.

In both the Esk and Upper Derwent catchments, there have recently been movements towards other, more sustainable options, which will address a wider range of issues regarding land management practices over the long-term. Authorities such as the National Park are now working hard with the land-owners in order to increase the uptake in Agri-Environmental Schemes such as Environmental Stewardship agreements. Specific options available in the catchments under the Entry Level Stewardship (ELS) scheme are: ditch management, buffer strips on cultivated or intensive grassland, infield grass to prevent erosion, maintenance of watercourse fencing and conversion to grassland. However, under this scheme, the land-owner has the right to choose the type and location of improvements to make in order to qualify for the maintenance payment. Further to these ELS agreements, Higher Level Stewardship (HLS) may also be suitable for targeting specific improvements in vulnerable areas within the catchments.

Chapter 4: Methodology

4.1 Introduction

Given the detailed examination of the methods available for the assessment of fine fluvial suspended sediment flux (Chapter 2), appropriate methods were selected to successfully address the objectives of this research. The same methodology will be applied in both the Esk and Upper Derwent catchments.

4.2 Monitoring Station Locations

Monitoring stations were installed at three locations in the Esk catchment namely on Esk at Danby, Esk at Glaisdale and in the Glaisdale Beck sub-catchment. One station was installed in the Upper Derwent catchment on the River Rye at Broadway Foot. Measured were river level and turbidity which are deemed important in the estimation of fine suspended sediment flux (Figure 4.1). These sites were equipped with a:

- Stage recorder - Druck PDCR 1830 Pressure Transducer (except Broadway Foot)
- Turbidity sensor - McVan Analite 395 Turbidity Probe (Range 0-1000 NTU)
- Automatic water sampler - ISCO / SIGMA automatic water sampler (see Table 4.1)
- Data logger - Campbell Scientific CR10X data logger, power source and solar panel

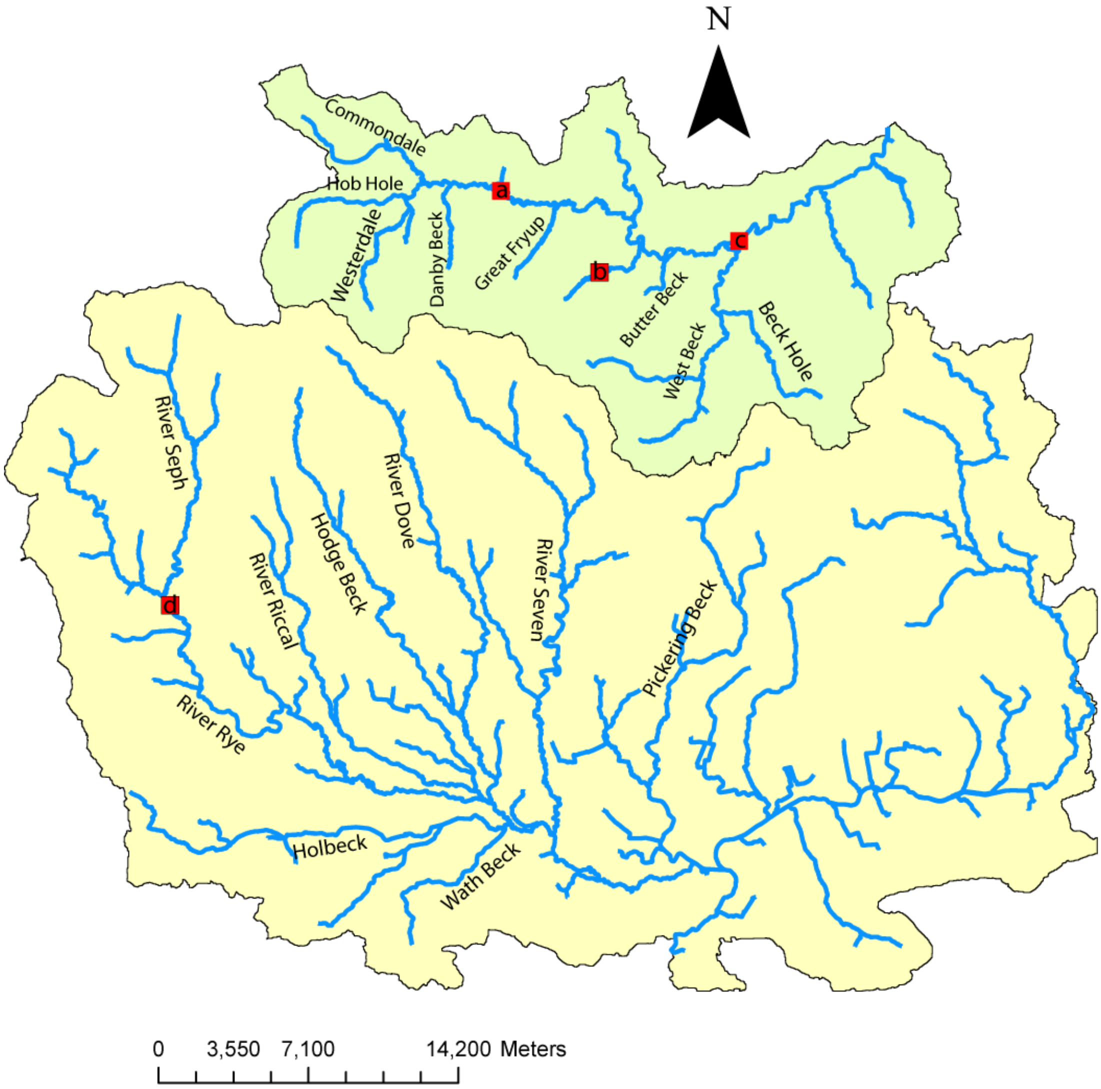

Figure 4.1 Location map of the monitoring stations in the Esk and Upper Derwent catchments. The Esk catchment is shaded green and the Upper Derwent yellow. The following letters represent the corresponding monitoring stations (a) is the Esk at Danby; (b) is Glaisdale Beck; (c) is Esk at Grosmont; (d) is Rye at Broadway Foot.

4.3 Suspended Sediment Concentration Measurements

4.3.1 Application

A data logger (Campbell Scientific CR10X) was used to control and record measurements taken by the turbidity probe and pressure transducer. This data logger model is capable of storing up to 62,000 data points. This was powered by a 12V battery and solar charger in situations where access to the AC mains supply was not available. Instantaneous measurements of turbidity and pressure were recorded every 15 minutes.

In the field, probes were secured in 68 mm poly-pipe housing to prevent damage and limit the extent to which water-borne detritus could become trapped on the optical surface which would reduce the accuracy of measurements. The housing, consisted of a vertical pipe, attached to the river bank, which connected to a 90° elbow joint and smaller length of horizontal poly-piping which was submerged below the water surface and protruded out into the main flow of the river. The probe itself was recessed by 2 - 5cm within this smaller section.

The McVan Analite 390 Digital Series range of nephelometers used in this research comply with ISO 7027 standards (International Organisation for Standardisation, 1999) and are able to operate at depths of up to 100m. They operate by measuring the degree of scattering at an angle of 90° to the incident light beam using a near Infra-red photodiode light source with a wavelength of 860nm (0.86µm) and a spectral bandwidth less than or equal to 60nm with a path length under 10cm, providing accurate turbidity measurements in the range of 0 – 1000 NTU's with ± 1% precision.

This particular probe was chosen because of the range of turbidity conditions the probe would be exposed to in the field (Bracken and Warburton, 2005). A balance between the operational sensitivity and range was necessary. This probe also has the additional benefits of being insensitive to stray light and being equipped with an automatic wiper mechanism, therefore reducing the potential for bio-fouling of the optical surface.

Chapter 2 highlighted how the design of turbidimeters can have a significant effect on the resulting measurements. This variation can vary by up to a factor of two or even three in extreme cases (Anderson, 2004; Lewis, 2007). For example, Mc Van's Analite 395 Nephelometric turbidimeter has been found to produce measurements higher than those measured using the Hach OBS-3 turbidimeter. Despite these inherent differences between the probe outputs, it is possible to convert the output to an equivalent value for another specified probe with errors of as little as 2% but maximum errors exceeding 100% with a mean error of 12% (Lewis, 2007). It is therefore important that the make, model and angle of measurement are specified when presenting results.

4.3.2 Lab Calibration

Prior to the use of the turbidity probes in the river channel it was necessary to assess their stability, sensitivity and linearity in relation to a known reference so that any instrument drift or deviations between the response of different probes could be documented and accounted for (Minella et al., 2007). There is no standardised method for testing these attributes, although, a commonly used approach involves measuring the output of the probe against varying concentrations of Formazin ($C_2H_4N_2$) solution. The internal configuration of the chosen probe means that the probe should exhibit a linear response to Fomazin up to a maximum turbidity value of 1000 NTU. It was therefore deemed sufficient to calibrate the probes up to a maximum Formazin value of 1000 FTU which is equivalent to SSCs of between 813 and 1241 mg L^{-1} depending on the individual monitoring location. In some cases, where the turbidity probe is less sensitive at the higher range of turbidity values, some minor extrapolation of the fit may be necessary. Once calibration with the Formazin solution is completed, the readings generated by each probe can be compared.

In order to successfully assess the stability and consistency of turbidity readings under known standards, a laboratory experiment was conducted. A 5 litre beaker was used as the vessel in which the Formazin solution was contained and this was placed on a magnetic stirrer with a variable motor. The turbidity probe was connected to a Campbell Scientific CR10X logger and suspended into 4 litres of Formazin solution at a concentration of 1000 FTU. Complete mixing was ensured by using a magnetic mixer. Measurements were taken at 0.5 the depth once per minute for five minutes, allowing any drift / deviation to be assessed. This was completed for each of the five probes calibrated. Having calibrated all of the probes to 1000 NTU, the next standard of Formazin was produced by diluting the original Formazin solution. This was achieved by engaging the motor on the magnetic stirrer and siphoning off a known volume of solution from the beaker. This was taken at 0.5 of the depth. Once this was completed, the same volume of deionised water was added back to the beaker as had been removed, effectively diluting the mixture to the specified concentration whilst maintaining 4 litres of Formazin solution. Following the successful creation of the new mixture, the turbidity of the solution was measured using the identical method as previously described. This method was repeated in order to provide calibration measurements at the intervals of 1000, 900, 810, 721, 631, 540, 450, 360, 270, 180, 90, 68 and 34 FTU (Figure 4.2)

The degree of linearity in the probes response to increasing Formazin concentrations significant ($P < 0.001$). The gradient of the regressions for all of the probes are also similar, ranging from 0.9641 – 1.134. This highlights the comparable responses to changing Formazin concentrations. No drift was observed during the experiment and a small standard deviation of observations was recorded. Using the regression equation shown in the combined calibration, the turbidity meter outputs (NTU) were converted to FTU/FNU.

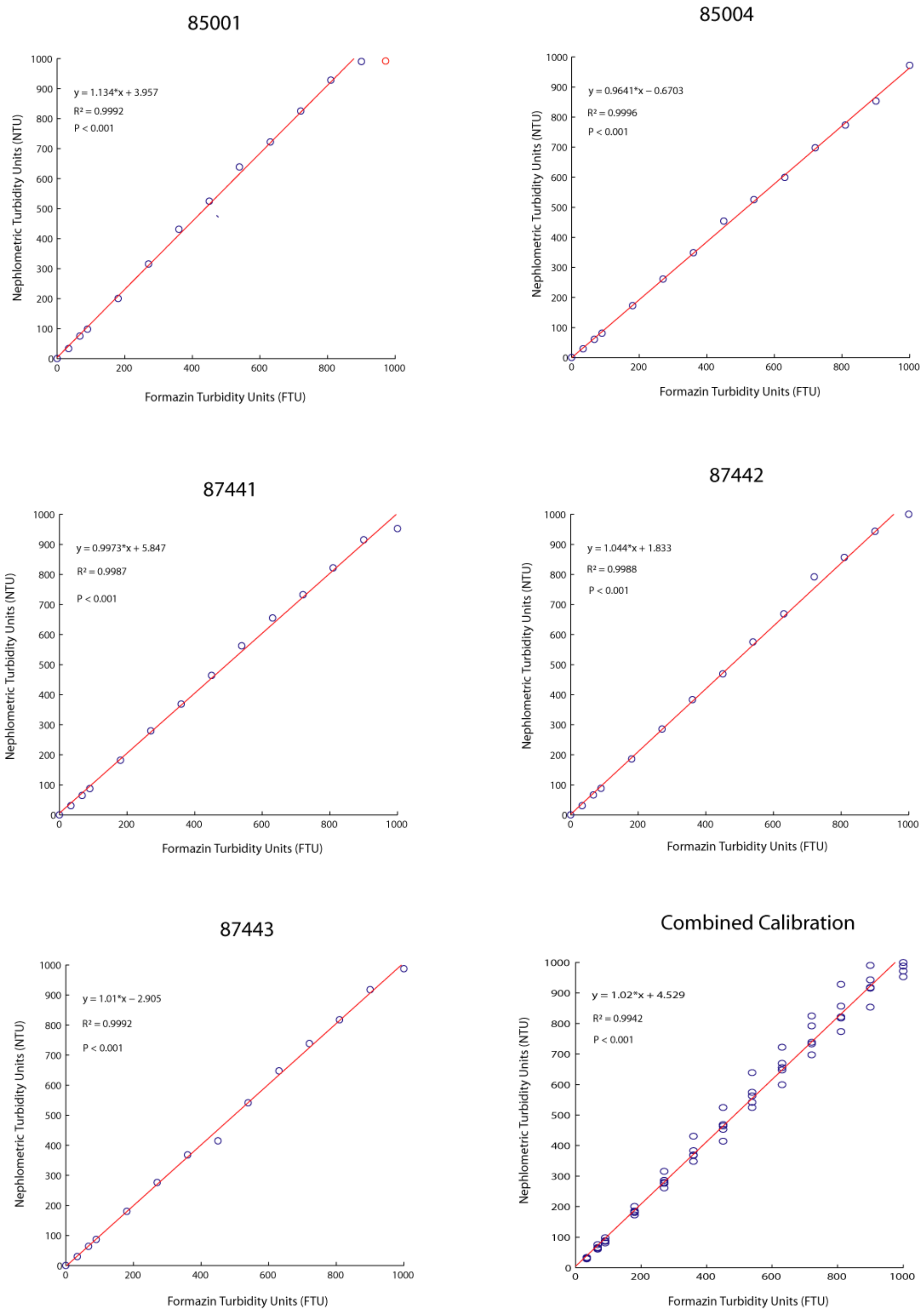

Figure 4.2: The linear relationships between the measured turbidity (NTU) and the concentration of Formazin solution (FTU) for all of the Analite 390 series probes.

4.3.3 Field Calibration

In addition to accounting for instrument drift or deviations between the responses of different probes, it is also important to account for varying properties of the suspended sediment (e.g. particle size) described in Chapter 2 which could complicate the turbidity – SSC relationship in the field. In order to achieve this, relationships between turbidity and SSCs were assessed over a two year period at each of the turbidity monitoring sites (Figure 4.1) in order to capture some of the variability in sediment properties and incorporate this uncertainty in SSC estimates.

For this calibration method to be accurate there must be sufficient numbers of simultaneous suspended sediment concentration and turbidity measurements across the entire range of conditions throughout the monitoring period. To achieve this, automatic water samplers were deployed at the field sites (see Table 4.1):

Location	Sampler 1	Sampler 2	Auxiliary Equipment
Esk at Danby	Hach Sigma 900 Max	ISCO 6712	Storm sampling switch
Esk at Glaisdale	ISCO 6712		Storm sampling switch
Esk at Grosmont	Hach Sigma 900		Storm sampling switch
Rye at Broadway Foot	ISCO 6712		

Table 4.1: Details of the automatic water sampling equipment at each of the monitoring stations

Each sampler was equipped with 24 polyurethane bottles which were thoroughly cleaned and rinsed with deionised water prior to use. The ISCO 6712 and Hach Sigma 900 Max were equipped with 1 litre bottles, whereas the smaller Hach Sigma 900 was only equipped with

500ml bottles. The samplers were located 5 - 10m away from the main channel to minimise this risk of flood waters damaging the equipment or samples. The tubing which ran from the sampler into the river was 1cm in diameter, reinforced and protected. This tubing was attached to a steel boom which was secured to the bank and protruded ~1m into the main flow of the river at 50% of the river depth under base flow conditions. Prior to each sample, the tubing was purged of all water so there was no cross-contamination between individual samples. Ideally the intake would have faced upstream (Navratil et al., 2011). However, debris fouling and the inability to ensure that purging would be completed against a strong flow meant that the sampling intake was fixed perpendicular to the direction of flow.

At sites with two samplers, one was set up to act as a base flow sampler i.e. sample every 6 hours from the initiation until the last of the bottles were filled, with the second sampler being initiated only during significant rises in the river level. This sampling threshold was adjusted depending on the need to collect SSC samples at specific flow magnitudes. At sites where only one automatic sampler was installed with a storm sampling switch, sampling was controlled by rises in river level whereas sampling largely occurred at fixed intervals of 6 hours where the storm sampling switch was not available.

In addition to the auto sampling programme, manual dip sampling of the river to determine the SSC was also completed. This was typically conducted during regular site visits to ensure ample numbers of base flow samples. Samples were extracted using a 1 litre water bottle immediately downstream of the turbidity probe to ensure that calibration samples were consistent with the location the turbidity measurements were taken.

Upon collection of the known volume of water-sediment mixture samples (from the autosamplers / manual sampling), they were processed to determine the suspended sediment concentration (mg L^{-1}) using a methodology consistent with the requirements stipulated by Test Method B of the ASTM Standard Test Method D 3977-97 (American Society for Testing and Materials (ASTM) 2000). The samples were gravimetrically filtered through pre-weighed Whatman grade 934AH, 24-mm-diameter papers with pore sizes of 1.5 µm. Following filtration, the papers were dried at 103° ± 2° for 24 hours before being reweighed. The concentration was then calculated:

$$SSC = \sum \frac{M}{V}$$ **Equation 4.1**

Where: SSC = Suspended Sediment Concentration (mg L^{-1}); M = Mass of sediment retained by the filter paper (mg) and; V = Volume of water in the SSC sample (L).

For each monitoring site, the measured turbidity (FTU) and SSC pairings were plotted and a linear regression model was adopted to best describe the fit between the variables. Samples collected both manually and automatically are included in the model with an assumption of zero bias between the sampling methods. A condition set for the model was that the intercept had to pass through zero. This was chosen given that in filtered, deionised water, there should be no particles available to scatter the incident beam and therefore the turbidity should be 0. In total, 779 SSC samples were used for calibration across the four sites. Although every effort was made to sample the entire SSC range, some extrapolation of the fit at the higher ranges may be necessary. For Danby, Grosmont and Broadway Foot monitoring stations 76, 60 and 39% of the SSC range were sampled, whereas at Glaisdale Beck 100% of the range was sampled. Further to the development of the linear models, the uncertainty of the regression coefficients was evaluated, providing a measure of uncertainty in the calibration. This was achieved using a bootstrap re-sampling method. This method randomly re-samples the dataset *n* times, replacing the original sample and providing detailed information about the characteristics of the population. A sufficient number of re-samples is 2000 (Trauth, 2010), although in some instances 100000 samples have been used (Bilotta et al., 2010). In this instance, *n* is set at 2000. The results of the site specific field calibrations between turbidity and suspended sediment concentrations can be seen in Figures 4.3 – 4.6:

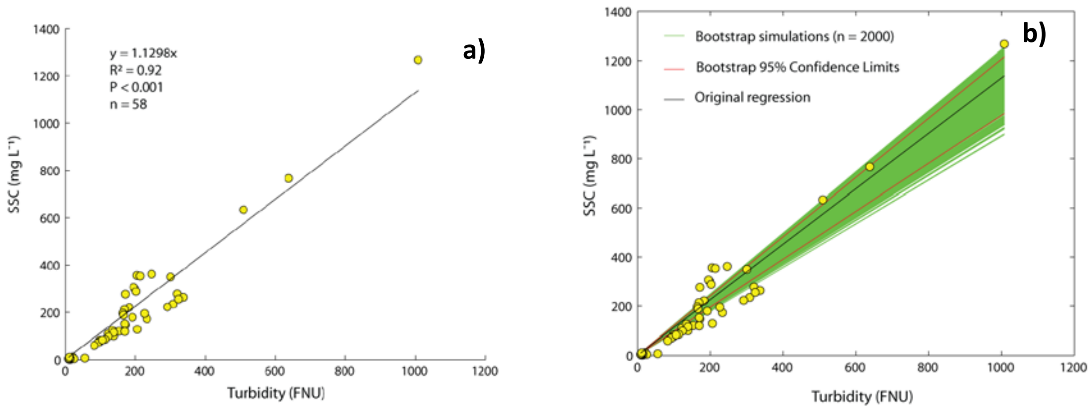

Figure 4.3 (a) Field calibration between turbidity (FTU) and SSC and; **(b)** Application of the bootstrap re-sampling method for Glaisdale Beck, Esk catchment

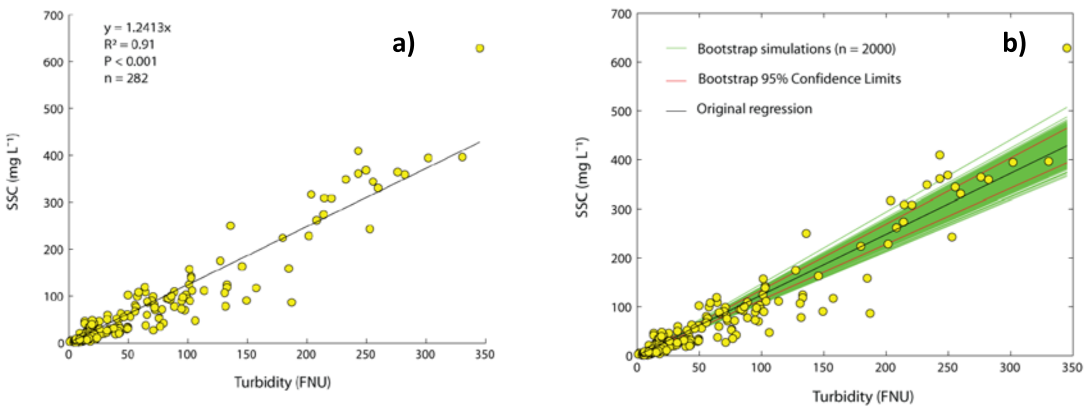

Figure 4.4 (a) Field calibration between turbidity (FTU) and SSC and; **(b)** Application of the bootstrap re-sampling method for the River Esk at Danby

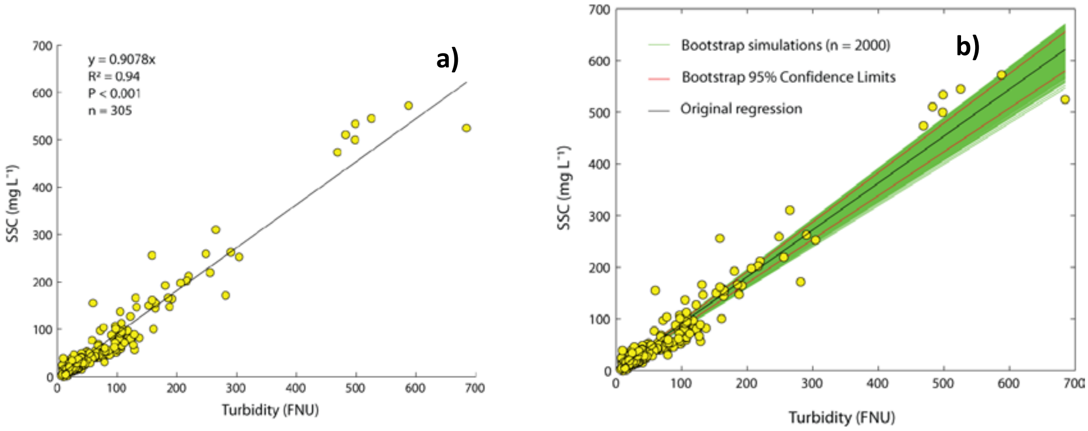

Figure 4.5 (a) Field calibration between turbidity (FTU) and SSC and **(b)** Application of the bootstrap re-sampling method for the River Esk at Grosmont

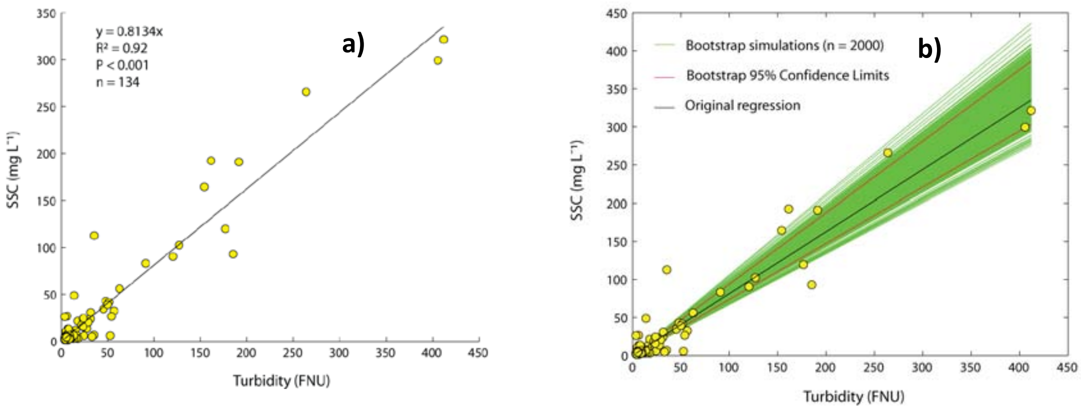

Figure 4.6 (a) Field calibration between turbidity (FTU) and SSC and **(b)** Application of the bootstrap re-sampling method for the River Rye at Broadway Foot

Lewis and Eads (2001) found that the correlation between turbidity and SSC tends to be strongest in watersheds with fine-grained sediments and indeed this appears to be correct for the calibrations carried out in the Esk and Upper Derwent catchments. However, there are other influencing factors such as the sample size and distribution of samples over the entire flow period, which may exert a significant impact on the accuracy of regression models.

	Range in SSC ($mg\ L^{-1}$)	Upper Confidence Limit of b coefficient (95%)	Lower Confidence Limit of b coefficient (95%)	Error/Accuracy (95%)
Glaisdale Beck	1.65 - 1266.20	1.2058	0.9762	22.96%
Esk at Danby	0.87 - 628.86	1.3426	1.1377	20.49%
Esk at Grosmont	0.37 - 572.6	0.9582	0.8471	11.11%
Rye at Broadway Foot	1.23 – 321.44	0.9304	0.7380	19.24%

Table 4.2: Summary of turbidity calibration parameters

4.3.4 Sensitivity of Turbidity Measurements to Sediment Particle Size

Given the well documented and observed changes in turbidity measurements to varying fine suspended sediment properties, it was deemed worthwhile to test the response of the turbidity probe under the range of operating conditions which the probe is likely to be exposed to in the field (e.g. Minella et al., 2007; Pavanelli and Bigi, 2005). This was achieved in a controlled lab setting by varying the median particle size of the suspended sediment sample at known SSCs. Typically in experiments such as these, material proximal to the river channel (e.g. bed and banks) is often used. However, in reality, this may not be representative of the transported material since it has been shown that a significant proportion of transported fine sediment could be derived from distal locations in the catchment (e.g. Klein, 1984). Therefore for the purposes of this test material which had been captured by in situ TIMs was used.

Since the turbidity probes in operation are believed to be insensitive to water and sediment colour and temperature, and given that the spatial variability in organic content between the sites does not vary appreciably, the impacts of sediment samples of differing median particle size is tested through a laboratory experiment. This might explain why the regression coefficients for each of the site specific field calibrations differ.

Firstly, in order to characterise the sediment which had been trapped by the samplers, particle size analysis was conducted. The recovered sediment was dried at 40°C and then lightly disaggregated using a rubber bung. A mass of between 0.3 and 0.5g of sediment was subsequently sub-sampled for analysis using a riffle box. This sample was prepared for analysis by treating it twice with 20ml hydrogen peroxide to remove all organic material, followed by the addition of 2ml of sodium hexametaphosphate. The sample was then left for 24 hours to allow the particles to deflocculate. Samples were then analysed using a Coulter laser granulometer (LS230) to determine the absolute particle size.

This sediment was dried, and then sub-sampled so that 4 – 5g of sediment was available for use in the calibration of the probes with reference to known SSCs and particle size distributions (PSD's). Four samples of contrasting particle sizes, representing the extremes of the sediment particle size transported in these catchments were chosen for this experiment. The four samples had median particle sizes of 7.37µm, 40.8µm, 146µm and 251.1µm. Each of the turbidity probes were calibrated to the specific particle size fraction across the entire range of turbidity values which could be expected to be observed under operating conditions. The results of the experiment are shown in Figure 4.7.

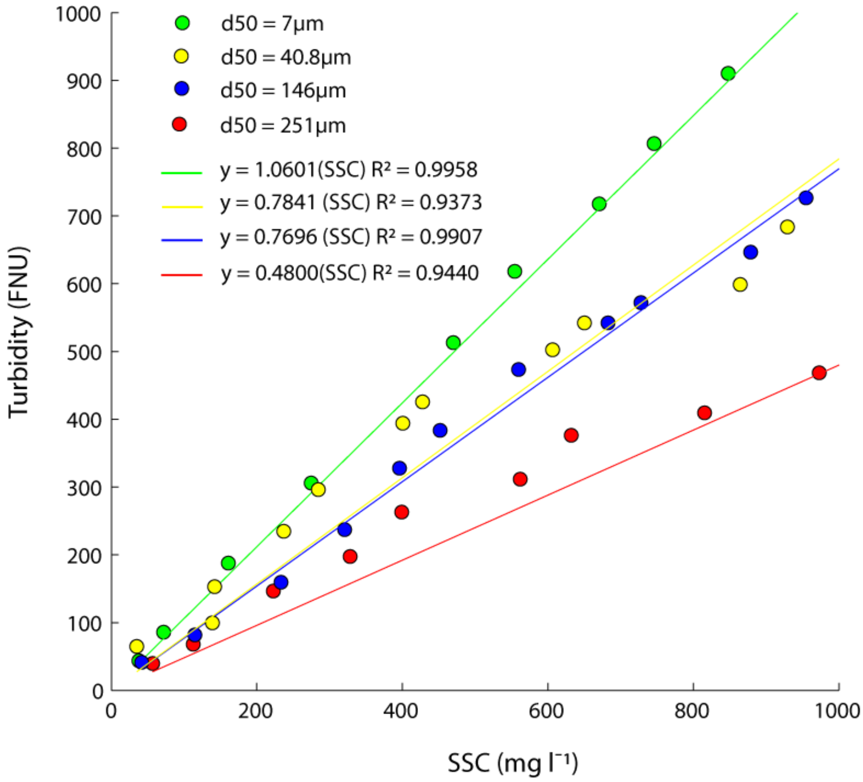

Figure 4.7: Variations of turbidity response to varying particle size characteristics

This shows a distinctly varied response caused by varying the particle size of sediments. This accounts for some of the variation in the slope values for field calibration between SSC and turbidity. However, it is clear that the greatest sensitivity to particle sizes occurs in the fine (7µm) and coarse (251µm) fractions, with the turbidity signal being relatively stable within the middle ranges spanning (40.8 - 146µm). Although the developed turbidity – SSC relationship in the field does indirectly account for particle size effects, the variability on an event basis may not be captured entirely through field calibrations.

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4.4 Discharge Estimations

In addition to measuring the suspended sediment concentrations flowing through each of the monitored sub-catchments, estimates of the river discharge were also required. In the Upper Derwent catchment river discharge was monitored at high frequencies at the Broadway Foot gauging station. However, in the Esk, the flow was not gauged and therefore the development of stage-discharge rating curves was necessary.

The river stage was measured at 15 minute intervals using Druck PDCR 1830 pressure transducers. This is a compact device with a length of 96 mm and diameter of 17.5 mm, ideal for use in applications where space is a constraint. This specific model is designed for depth measurements in water ranging from 0 - 3.60 m with a pressure range of 350 mB. The probe is rugged and capable of operating at temperatures of - 20°C to + 60°C whilst providing stable measurements within ± 0.1 % of the maximum output (Campell Scientific, 1996). At each site the pressure transducer was fixed to a length of rebar which was securely fastened to the inside of the stilling well.

In addition to the river stage, the mean velocity of the channel was also required for the full range of within-channel stage values. This was approximated using Manning's flow resistance Equation 4.1. This method suggests that the velocity of the river can be approximated through the use of the river gradient, hydraulic radius and *n*, which represents the energy loss encountered due to boundary friction.

$$V = \frac{k}{n} R^{0.67} S^{0.5}$$ **Equation 4.1**

Where V= mean downstream velocity ($m^3 s^{-1}$), k = 1 for SI units, R = hydraulic radius (m), S = energy gradient (m/m) and n = Manning's roughness coefficient.

The hydraulic radius and energy gradient properties of the river passing through the monitoring location were directly measured using an Electronic Distant Measurement total station (EDM) which is capable of measuring the vertical component of a coordinate to within 5 mm.

The n parameter can be determined directly where velocity measurements are taken at known stages; however the predicted roughness coefficient is likely only to be applicable for that river flow given that the hydraulic roughness has been shown to decrease with increasing stage. It is more common for the *n* value to be determined through the use of tables and reference photos of rivers with a known average measured *n* with this then being modified to account for the studied river reach. The method utilised here is that proposed by Cowan (1956):

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m$$ **Equation 4.2**

where:

n_b = base value of n for a straight, uniform, smooth channel in natural materials,

n_1 = correction for the effect of surface irregularities,

n_2 = correction for variations in cross section size and shape,

n_3 = correction for obstructions,

n_4 = correction for vegetation and flow conditions and

m = correction for degree of channel meandering.

Using this information, stage-discharge rating curves were developed in order to provide an approximation of the discharge for a given stage (Table 4.3)

Stage (m)	Danby Estimated Q ($m^3 s^{-1}$)	Glaisdale Estimated Q ($m^3 s^{-1}$)	Grosmont Estimated Q ($m^3 s^{-1}$)
0.2	0.31	0.03	0.1
0.4	0.45	0.2	0.48
0.6	0.98	0.52	1.59
0.8	1.70	0.96	3.56
1	2.60	1.49	6.24
1.2	3.69	2.08	9.75
1.4	4.95	2.74	13.88
1.6	6.38	3.45	18.1
1.8	7.98	4.22	23.08
2	9.76	4.94	28.91
2.2	11.70	5.29	35.35
2.4	13.82	6.39	41.92
2.6	16.09		
2.8	18.53		
3	21.13		
3.2	23.88		

Table 4.3: Developed rating relationships between river level and discharge using Manning's flow resistance equation

4.5 Suspended Sediment Load Calculations

Given the successful establishment of a suspended sediment concentration and river discharge time series for each of the monitoring stations, the mass of sediment being transported through the reach can be calculated. The mass of sediment for each of the [SSC, Q] pairings is calculated, providing the sediment load for the sampling interval:

$$iSL = \int_0^t K \cdot SSC \cdot Q \, dt$$ **Equation 4.3**

where: iSL = Interval sediment discharge (t); K = unit conversion factor; SSC = instantaneous suspended sediment concentration (mg L^{-1}) and; Q = Discharge ($m^3 s^{-1}$).

This interval suspended sediment load is then added to additional interval suspended sediment loads, allowing the establishment of the total suspended load for the period of interest.

$$SSL = (SL_1 + SL_2 \cdots SL_n)$$ **Equation 4.4**

Where gaps in the SSC and Q data exist, it is not possible to directly calculate the iSL. When this occurs, the first option is to interpolate the missing data series on occasions where:

1. The missing data period is short i.e. < 1 hour or
2. The river is dominated by base flow for the duration of the missing data period.

However, on occasions where this is not the situation and it is the SSC data which are missing, a synthetic time series will be created using the appropriate rating curve model which best fits the catchment and stage on the hydrograph (Chapter 6). This was only implemented when the model predictions were significant at the 95% level. Due to the effective rating relationships developed, the SS loads for all missing data periods were successfully modelled.

The estimation of SS loads using the adopted method is one of the most widely and successfully used; however, the following components of the calculation may act as sources of error thereby reducing the precision of the load estimates: (a) the frequency of sampling;

(b) the representativeness of point measurements; (c) technical problems resulting in missing data; (d) effectiveness of SSC calibrations; (e) suitability of the chosen turbidity probe for the environmental conditions; (f) quantification of external effects (e.g. particle size variability, organic content etc.); and (g) discharge estimations. Errors associated with each of these components will be propagated through to the final SS load estimations. In a recent review of the global uncertainty associated with this method of estimating flux, Navratil *et al.* (2011) found associated error to be up to 29% with an assumed discharge uncertainty of 20%.

4.6 Mass flux Sampling

In order to successfully monitor the flux of fine suspended sediment across the research catchments, including along the main river and all major tributaries, time-integrated sampling was undertaken. This allowed over 40 monitoring locations to be established, providing good spatial coverage. IN order to achieve this time-integrated approach TIMs were deployed. These have been regularly used for sediment fingerprinting studies in temperate, tropical and sub-arctic conditions (Fox and Papanicolaou, 2007; Hatfield and Maher, 2008; McDonald et al., 2010; Onda et al., 2007; Phillips et al., 2000; Walling et al., 2008b), and given its relative popularity it has also received some appraisal of its ability to capture a representative sample of fine suspended sediment (see Section 2.6.4).

The installation the TIMs in the catchment occurred during a period of low flow on the 21st September 2007. An additional four sites were installed on Glaisdale Beck on the 26th September 2007. In the Upper Derwent catchment, they were installed in two batches due to difficulties in achieving consent for a number of the sites. The first batch was installed on 16th August 2008 with the second batch being installed on the 16th September 2008.

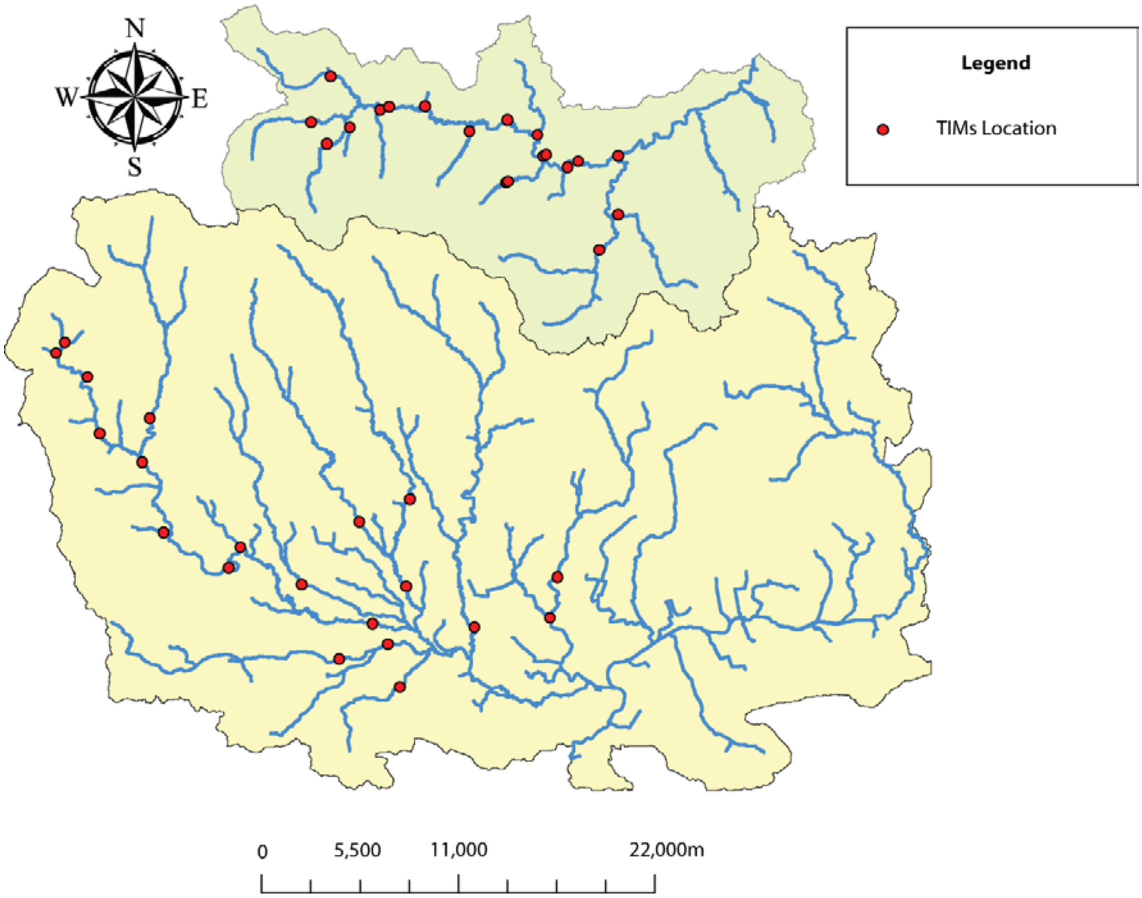


Figure 4.8: Location map of the TIMs sites in the Esk and Upper Derwent catchments

The procedure for installing the TIMs was to firstly secure two vertical rebar stanchions into the river bed in the centre of the river channel so that they would be stable even during high flow periods when the river bed may be mobile. Heavy duty cable ties were attached to the eyelets which had been welded on to the stanchions. The TIMs sampler was then fixed between the two uprights and securely fastened. Care was taken to ensure that the sampler inlet and outlet were perpendicular to the flow and fully submerged at the time of installation. In the locations where two samplers were installed at the same monitoring location for validation purposes, the samplers were positioned adjacent to each other with a gap of at least 0.5m (to avoid flow interference), whilst still being located roughly in the centre of the channel.

It was the initial aim to collect the sediment which had been trapped by the TIMs following every significant storm in the catchment. However, it became clear that this may not yield a sufficient mass of sample for subsequent laboratory analysis, nor would it be feasible given the frequency of runoff events and the time demands of other fieldwork and lab activities. Samples were therefore recovered on an approximately monthly basis to provide a sufficient mass of fine sediment for analysis, whilst having a sampling period not too great to preclude analysis of spatial variations of sediment transfer over different periods of the year.

During collection of the TIMs, the device was removed from the stanchions with the sediment trapped emptied into a clean 5L container. The sampler was rinsed and returned back into position in the river. The samples were taken back to Durham University and stored in a refrigerator for 4 days to allow the fine sediment to completely settle to the base of the container. The water was then siphoned off and discarded, taking care not to disturb the sediment. Although this siphoning process has the potential to lose sediment, preliminary analysis showed that the supernatant contained on average 0.12% of the total mass of collected sediment. The sediment was removed from the container into a 2L beaker. All of the sediment was washed out of the container and into the beaker. The 2L beaker was then placed in an oven at 40°C for 24 hours before the water was again siphoned off and placed back in the oven allowing the sediment to completely dry. Following this, the sediment was removed from the beaker and gently disaggregated using a rubber bung before being passed through a 2 mm sieve. Only organic material failed to pass through. The fine sediment was then ready for subsequent analysis.

4.6.1 Suspended Sediment Load Estimation

Given that the TIMs by their nature are time integrated, the mass of sediment they capture reflects the cumulative fine suspended sediment flux for the 12.56cm^2 cross-section of flow which enters the sampler through the inlet nozzle. If it is accepted that this is representative of the ambient flux (see Annex A), the flux of material captured must be scaled by a factor which represents the cross-sectional area of flow during the monitoring period:

$$rSSL = K \cdot M \cdot ScE \qquad \textbf{Equation 4.5}$$

Where: K = Unit conversion factor; M = Mass of sediment captured (g); ScE = Scaling exponent.

In this research, a static scaling exponent, based on the bank-full cross-sectional area of flow was used:

$$ScE = \frac{CSA}{ID} \qquad \textbf{Equation 4.6}$$

Where: CSA = Bank-full cross-sectional area (m^2); ID = Inlet diameter (m^2).

In addition to utilising the TIMs as a means of estimating fine sediment flux, further analysis of the trapped fine suspended sediment was also performed. Results presented are restricted to absolute particle size analysis and organic content. The process involved in the assessment of these sediment properties is explained below.

4.6.2 Particle Size Measurements of Suspended Sediment

In order to assess the absolute particle size of the mineral material trapped by the TIMs, a mass of between 0.3 and 0.5 g disaggregated fine sediment was sub-sampled for analysis using a riffle box. This sample was prepared for analysis by treating it twice with 20 ml hydrogen peroxide to remove all organic material, followed by the addition of 2 ml of sodium hexametaphosphate. The sample was then left for 24 hours to allow the particles to deflocculate. Samples were then analysed using a Coulter laser granulometer (LS230) to determine the particle size. Analysis of the PSD (particle size distribution) was conducted twice per sample, with the average of the runs being taken. If visualisation of the data showed there to be considerable differences between the two sample runs, an additional two runs were completed, with the average PSD being taken without any anomalous runs.

4.6.3 Organic Content of Suspended Sediment

In order to determine the organic content of the fine sediment trapped by the TIMs, the sediment was subject to intense heating in a muffle furnace. When heated to 500 - 550°C, the organic matter present becomes oxidised to carbon dioxide and ash. The weight losses involved in these reactions has been shown to be closely correlated to the organic matter of the sediment, especially in clay-poor material (Heiri et al., 2001). Although this method is simple, it has been shown to provide the precision and accuracy of other, more complex geochemical methods (Dean, 1974).

In order to determine the organic content, the disaggregated sample of fine sediment, was initially sub-sampled using a riffle box so that approximately 5 g of sediment was available for analysis. This sample was placed in a pre-weighed crucible, the mass (g) of which is MC . The crucible was then placed in the oven at 105 °C for 24 hours to eliminate any moisture.

The crucibles and sample were then re-weighed, the mass (g) of which is MCS, providing us with a known mass of sample (MS) (g).

$$MS = MCS - MC \qquad \textbf{Equation 4.7}$$

The samples were then placed in a muffle furnace and heated to 550°C for 4 hours. The samples were then allowed to cool in a dessicator before being reweighed (g) (MAC). The mass of the ashed material (g) (Ash_{550}) was then calculated:

$$\mathrm{Ash}_{550} = \mathrm{MAC} - \mathrm{MC} \qquad \textbf{Equation 4.8}$$

From which the organic content (%) could be calculated:

$$LOI\%_{550} = \frac{MS - \mathrm{Ash}_{550}}{MS} \cdot 100 \qquad \textbf{Equation 4.9}$$

4.7 Chapter Summary

This chapter has identified the range of methods used to address the objectives of this research outlined in Chapter 1. The adopted field and laboratory methods used are consistent between research catchments and most suitable given the availability and accessibility of equipment. The data presented in the following chapters are a direct result of the range of techniques and approaches documented.

Chapter 5: Spatial Variability in the Physical Properties and Mass of Suspended Sediment Transfer

5.1 Chapter Overview

This chapter examines the spatial patterns of suspended sediment delivery and the physical properties of transported material in the river networks of the Esk and Upper Derwent catchments in North Yorkshire, highlighting transfer 'hotspots' which may be useful to determine areas of excessive suspended sediment transfer and target future management activity. The spatial variability in suspended sediment particle sizes and organic content of the material is also characterised. Figure 5.1 provides an overview of the framework for analysis which highlights each component of the chapter and the information this adds to the understanding of fine sediment transport dynamics. Synthesis of these distributed data using this novel approach will facilitate the development of conceptual models of fine suspended sediment transfer in the adjacent Esk and Upper Derwent catchments.

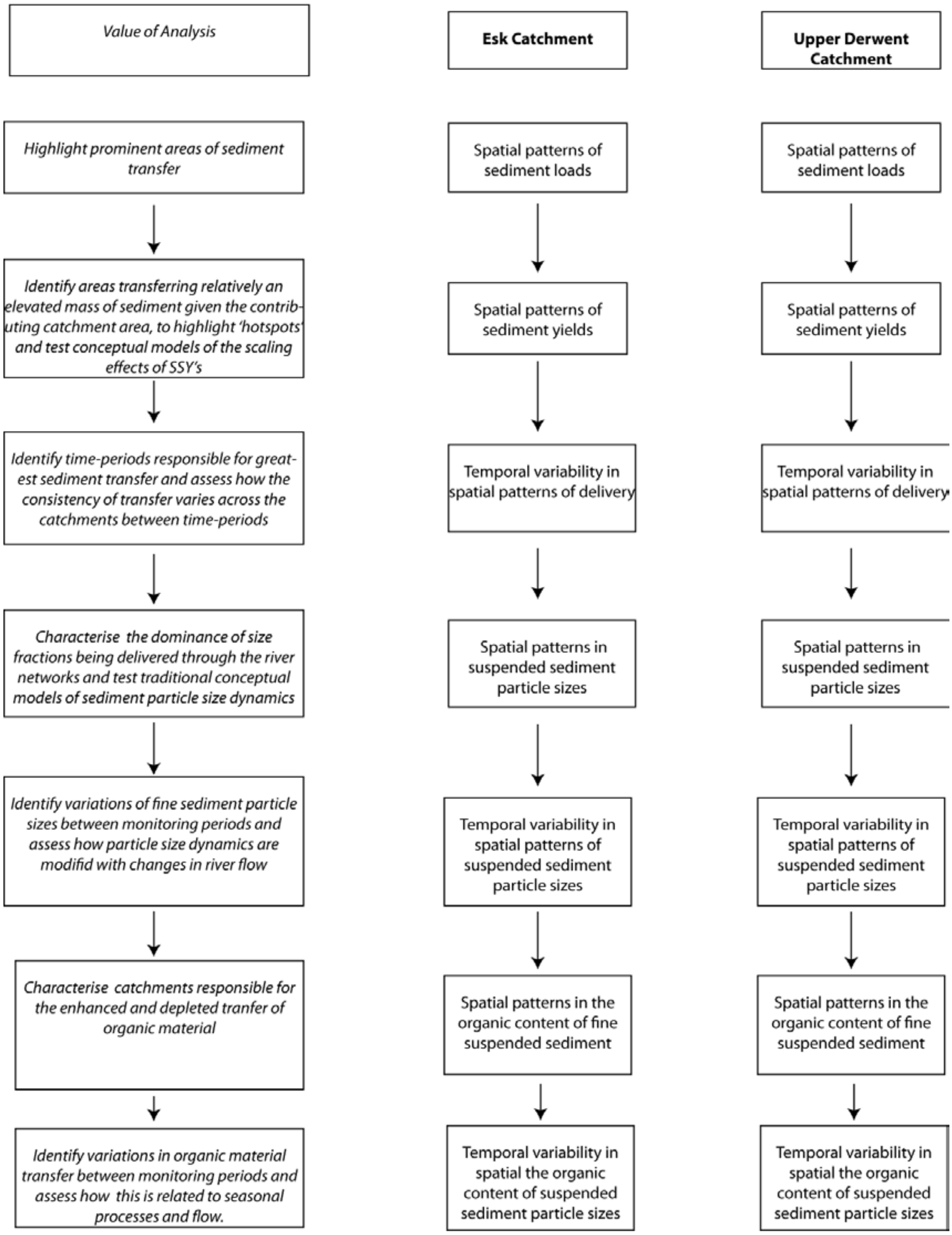


Figure 5.1: Framework showing the elements and linkages between analysed components of Chapter 5 and their contribution to understanding of sediment transfer in the Esk and Upper Derwent catchments

5.2 River Esk Catchment

Monitoring the spatial variation in the properties and flux of fine suspended sediment across the Esk catchment began on 21st September 2007 and continued through to 20th October 2009. The design of the TIMs sampling framework in the Esk catchment was designed to capture the broad spatial patterns of sediment transfer across the whole catchment, with all of the mapped tributaries being sampled as close to their confluence with the Esk River as logistically possible (Figure 5.2). This spatial representation of the catchment is displayed schematically in Figure 5.3 which highlights the location of the tributaries entering the main river and the distance of the confluence from the river source (in km).

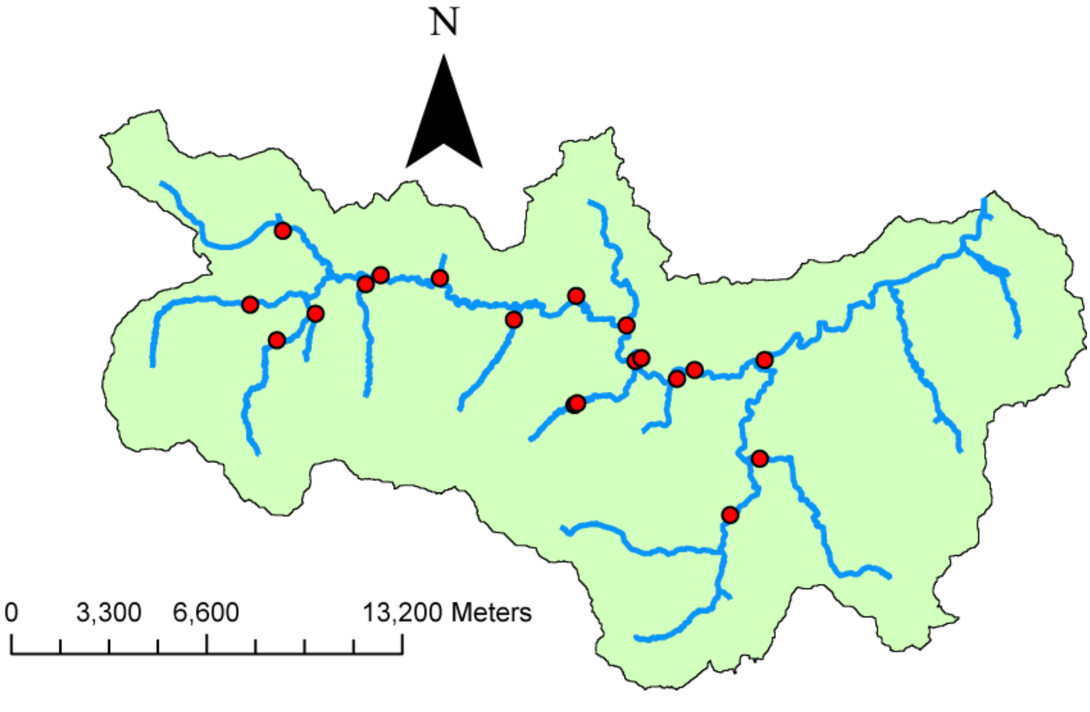


Figure 5.2: Location map of the TIMs sites in the Esk catchment. Red dots represent TIMs monitoring sites

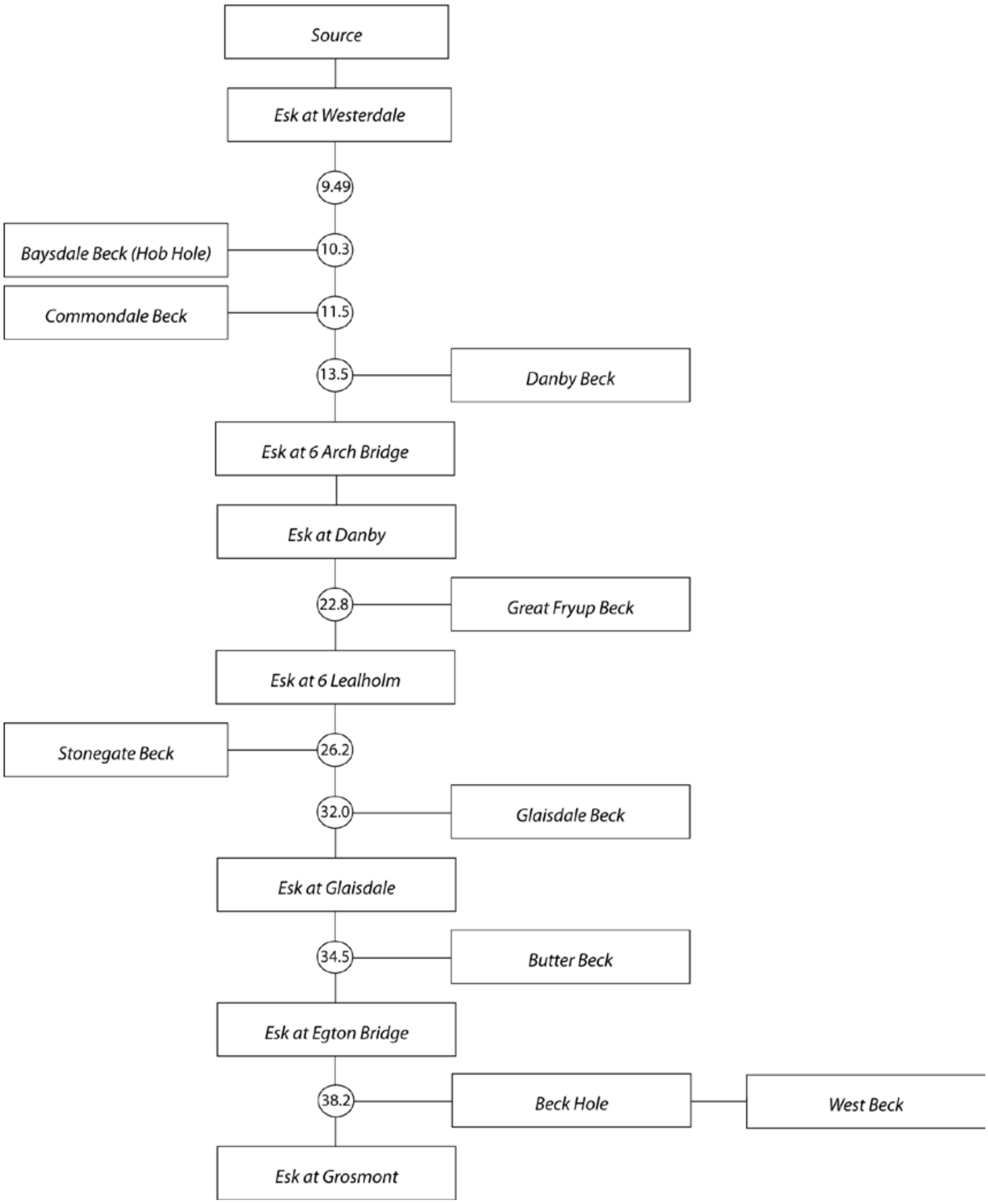
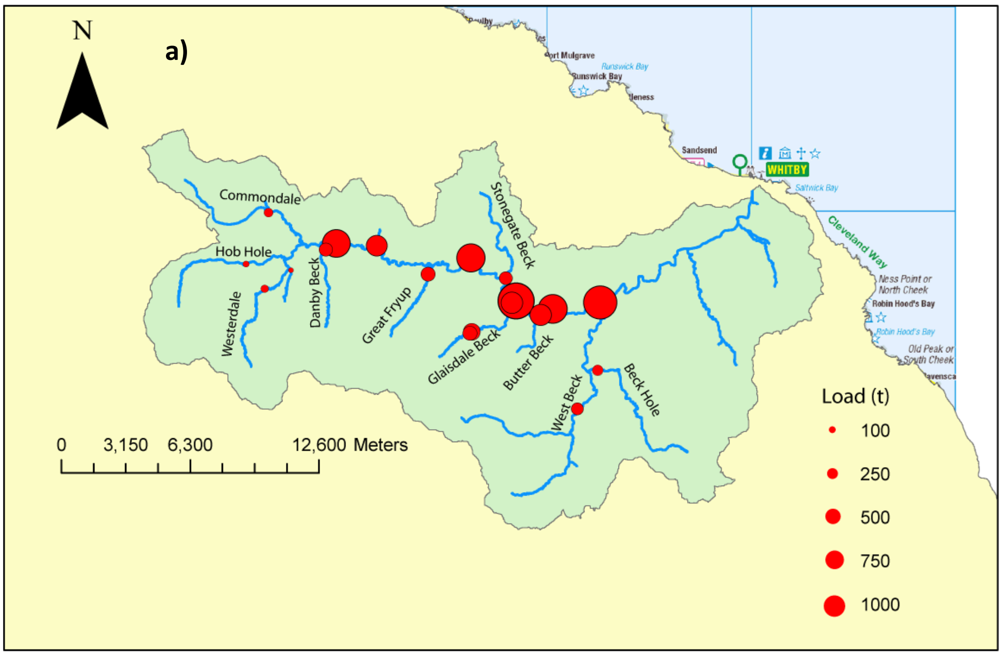


Figure 5.3: Schematic diagram of TIMs monitoring locations along the main Esk River and tributaries. Numbers in circles represent the distance (in km) from the river source.

5.2.1 Spatial Patterns of Suspended Sediment Flux

Patterns of spatial variability of fine suspended sediment transfer throughout the Esk catchment during the 2007/08 and 2008/09 hydrological years are presented in a range of formats including the relative load (t) and specific yields (t km^{-2}) at each point in the catchment. The specific sediment yield (t km^{-2} yr^{-1}) is assessed in relation to the catchment contributing area.

Figure 5.4a shows the between site variability of sediment loads (t) for the 2007/08 hydrological year. Generally as catchment contributing area increases, the annual suspended sediment load also increases. The mean loading is 862.42 t with a CV of 95.13%. The minimum annual load was measured at Tower Beck (51.96 t), whereas the maximum was obtained at Glaisdale on the main Esk river (2791.6 t). Although there is a general increase in sediment loads with catchment area, the loadings on some of the tributaries are somewhat more varied.



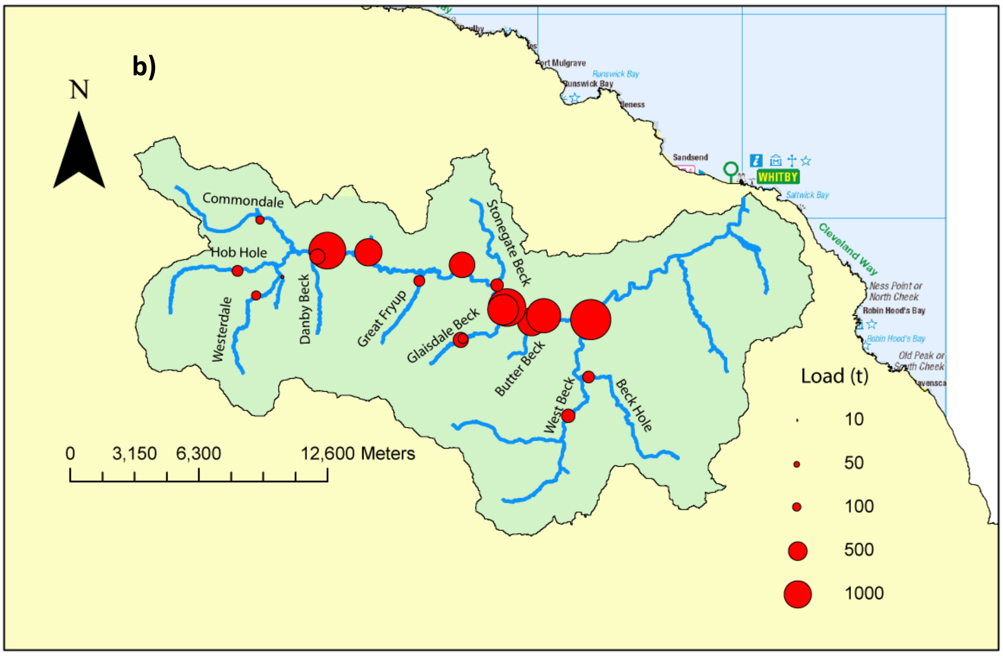


Figure 5.4: Annual suspended sediment load derived from TIMs samples during **a)** the 2007/08 and; **b)** 2008/09 hydrological years.

The mean annual load across the tributaries of the Esk river is 397.42 t (CV = 82.45%) with the largest of these loads occurs in Butter Beck (957.79 t), Glaisdale Beck (986.86 t), Danby Beck (374.80 t), Great Fryup Beck (428.75 t) and Stonegate Beck (366.33 t) whose catchment areas, range from 8.84 – 16.56 km^2. These loads are greater than those found at Hob Hole (80.50 t), Beck Hole (241.23 t) and West Beck (315.99 t) which have contributing areas of between 17.34 and 42.99 km^2. These sites producing low loads (relative to the mean tributary load) (with the exception of Beck Hole and West Beck which are located in the adjacent Murk Esk catchment) are located on the tributaries in the West of the Esk catchment; the very headwater catchments which join the main Esk River between 9.49 and 11.51 km downstream of the source in Westerdale. These headwater areas are heavily dominated by shrub heath; bracken and bog land types, with only Tower Beck consisting of any significant development of improved grassland (26% of total area). Conversely, the tributaries contributing the highest loads drain the central Esk valley, which join the main

Esk River between 13.50 and 34.52 km downstream of the source. These central areas of the catchment are largely dominated by improved grassland and to a lesser extent intensive agriculture. The catchments of the tributaries in the central Esk valley are also some of the steepest. For example, the average slope in the Great Fryup, Danby Beck and Glaisdale Beck catchments are 16%, 15% and 15 % respectively which are the three steepest in the entire Esk valley, whereas the headwater sub-catchments are slightly shallower with mean slopes of 15%, 14% and 13% for Tower Beck, Westerdale and Hob Hole respectively. The geology across the catchment is relatively homogenous, dominated by a mix of sandstone, siltstone and mudstone.

The between site variability of sediment loads over the course of the 2008/09 hydrological year is presented in Figure 5.4b. Again, this diagram demonstrates that generally as the catchment contributing area increases, the annual suspended sediment load also increases. The minimum annual load was again measured at Tower Beck (18t), whereas the maximum was obtained at the Esk at Grosmont (2239 t). The mean loading was 744t with a CV of 100.6%. The catchment average load decreased by 118 tonnes whereas the coefficient of variation increased slightly compared to the previous year when it was 95.1 %. Generally, between the 2007/08 and 2008/09 hydrological years the load is reduced in the headwater sub-catchments of the Esk (Figure 5.4) However two sites, namely Butter Beck and Glaisdale Beck stand out as having increases in sediment loads when the general trend is for a decrease. The largest reductions in sediment loads are observed between Lealholm and Grosmont along the main Esk River.

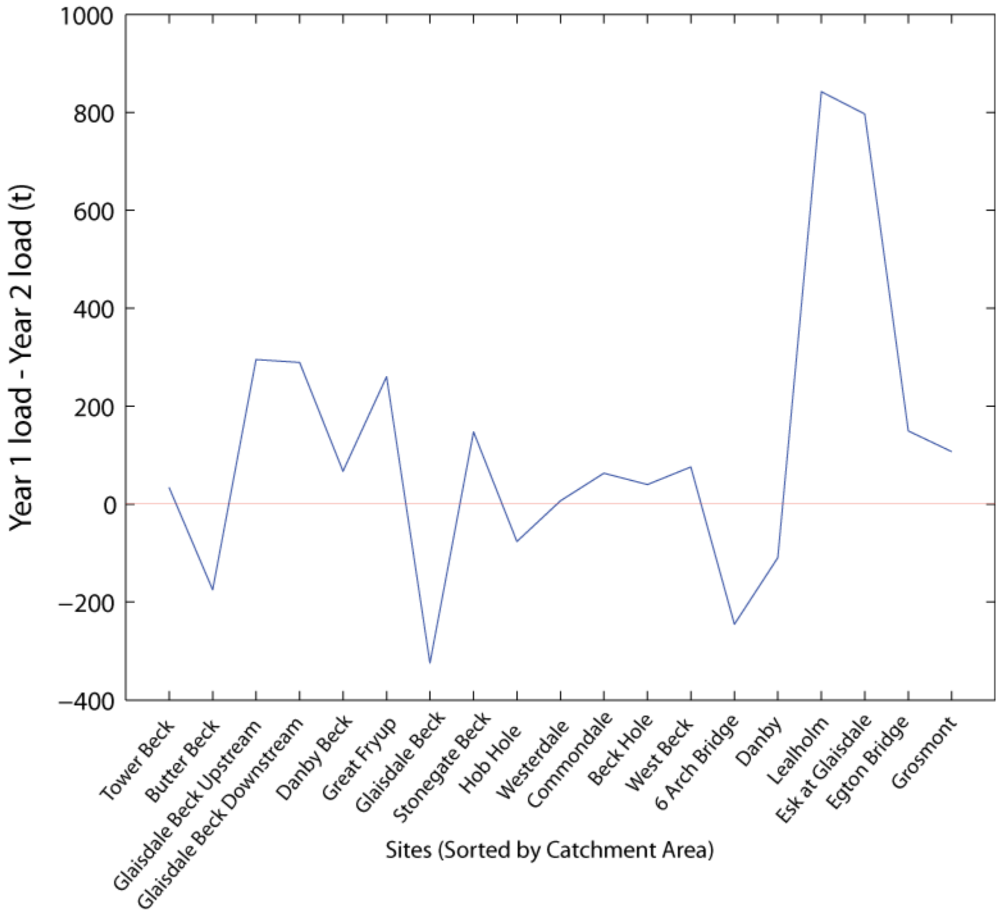
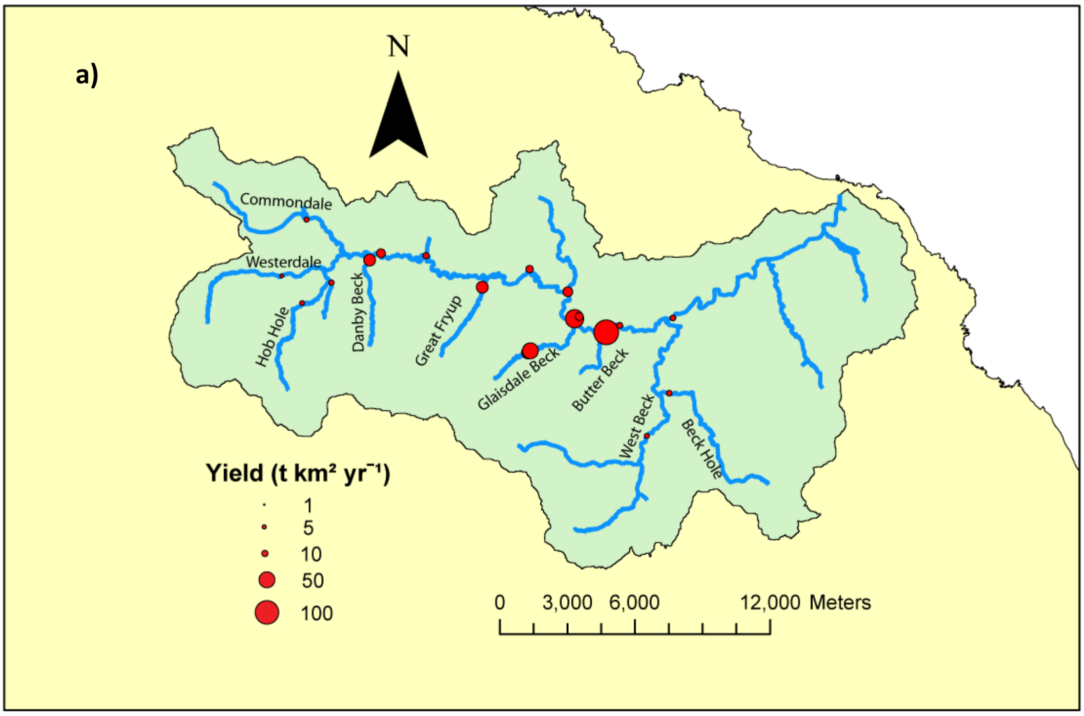


Figure 5.5: Differences between the annual suspended sediment load between the 2007/08 and 2008/09 for sites in the Esk catchment. The red line highlights the point of no change in the loadings between years

When these annual suspended sediment loads are transformed to represent the area-specific sediment yield (t km^{-2} yr^{-1}), a different pattern of sediment generation and transfer is apparent with the smaller sub-catchments generating a greater mass of suspended sediment per-unit area than the higher order streams (Figure 5.6).



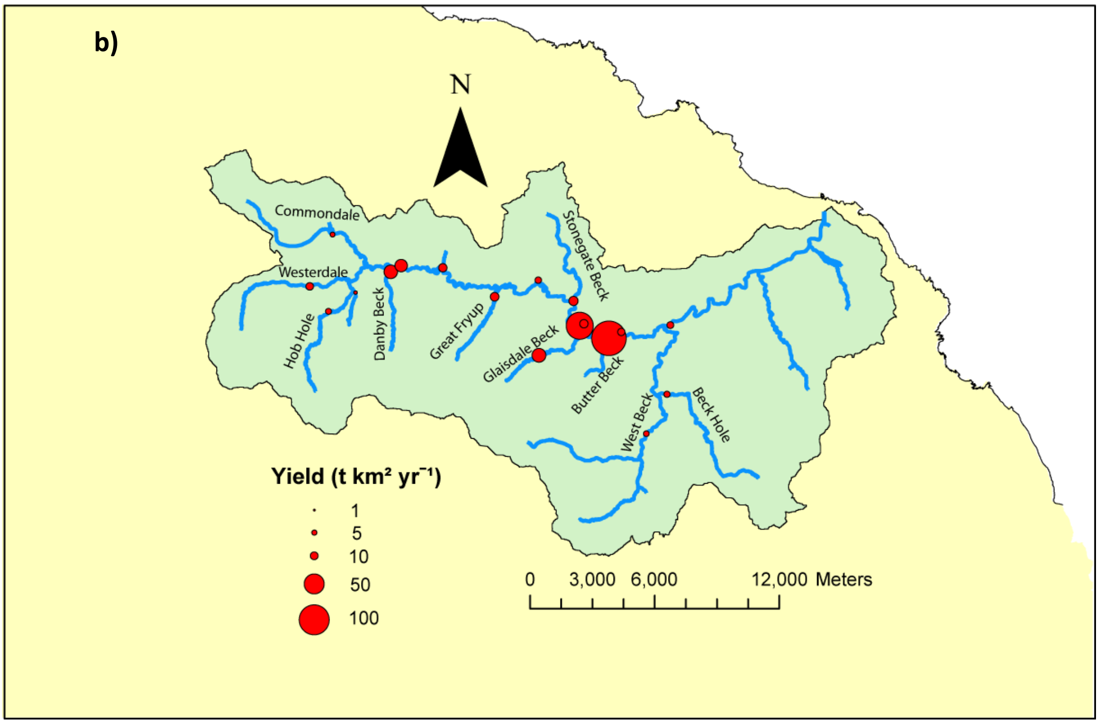


Figure 5.6: Annual suspended sediment yield derived from TIMs samples during **a)** the 2007/08 and; **b)** 2008/09 hydrological years.

Specific sediment yields are low at 8 and 3 t km^{-2} yr^{-1} in the 6.7km^2 catchment of Tower Beck which is smallest sub-catchment monitored. Specific yields then rapidly increase with increasing catchment area up to a maximum value of 108 and 129t km^{2} yr^{-1} in the 8.8km^{2} Butter Beck catchment. Specific yields remain high, but generally falling to a low of 22 and 13 t km^{-2} yr^{-1} in monitored catchments between the range of 11.6 – 16. 6 km^{2}. At the sites greater than 17.3 km^{2}, a plateau is reached with SSYs becoming relatively stable (Figure 5.7). For example, in the 2007/08 period, the SSY for catchment areas between 17.3 and 286.6 km^{2} range from between 4.6 and 18.7 t km^{-2} yr^{-1} with a mean value of 9.9 t km^{-2} yr^{-1} (CV = 43.7 %). In the 2008/09 period for the same sites this range is comparable at 4.3 – 21.6 t km^{-2} yr^{-1} with a mean value of 9.0 t km^{2} yr^{-1} (CV = 51.9 %).

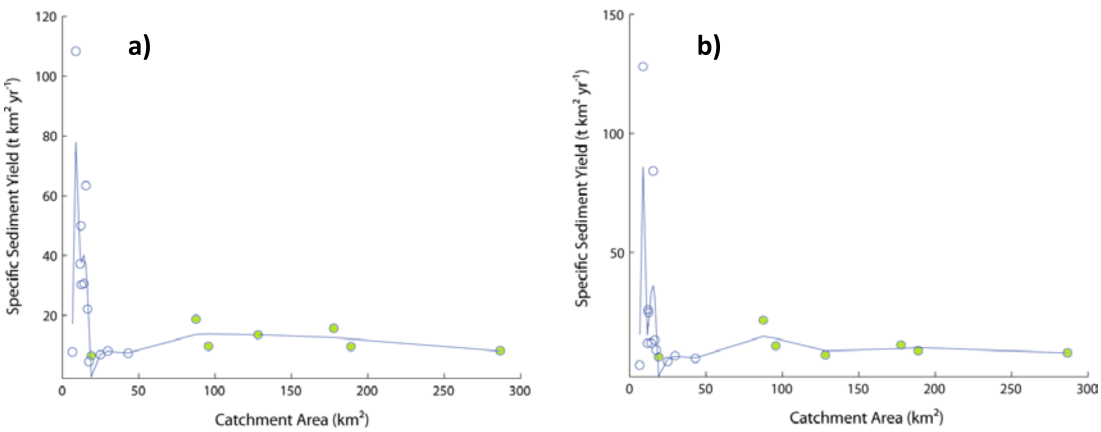


Figure 5.7: Scatter plot of contributing catchment area vs. specific sediment yield (SSY) with a superimposed LOWESS smoothing fit for a**)** 2007/08 and; **b)** 2008/09 hydrological years. Filled icons represent sites located along the main Esk River.

The finding that SSYs peak in the Esk catchment at the 8.84km^{2} catchment scale, along with the relatively high SSYs over the 8.84 – 15.56 km^{2} scales is consistent with previous research which has indicated that the peak in SSYs may vary occur anywhere within the range of 0.1 – 20 km^{2} (Osterkamp and Toy, 1997; Chaplot and Poesen, 2012; Poesen et al., 1996). Given that the peak in fine sediment loads occurs in these headwater sub-catchments of the Esk, some important points arise:

(a) At the scale of between 8.84 and 15.56km^2, linkages between the hill-slope and channel networks are likely to be well developed, with a high proportion of the catchment being well connected during storm events.

(b) Enhancement of flow from the North York Moors as a result of gripping of Glaisdale Moor, Baysdale Moor and Bransdale Moor is likely to have led to the enhanced conveyance of water through the landscape leading to higher peaks in flows and therefore greater potential for the generation of suspended sediment transfer (cf. Holden et al., 2004).

(c) This enhancement of flows will also produce greater shear stresses within the channel, potentially leading to channel incision and erosion of banks. Areas may be especially vulnerable which are unconsolidated; such as the tall, sandy banks adjacent in the Upper Esk catchment. Although any enhancement in shear stress may be propagated through the system, owing to the greater ratio of channel length: catchment area in the upper parts of the catchment, any effects would be biased towards these headwater areas.

Peak in SSYs, are often followed by a reduction in SSYs with increasing catchment area (de Vente and Poesen, 2005). This is a consequence of a decrease in local slope and the presence of wide floodplains creating sediment sinks (Walling et al., 1999; Syvitski et al., 2005; Birkinshaw and Bathurst, 2006). In the case of the Esk catchment between 17.34 and 286.57 km^2 the magnitude of transfer per unit area remains relatively consistent. Three factors explain this:

(a) Enhanced fine sediment inputs to the lower reaches of the main Esk River from tributaries of the central Esk valley e.g. Butter Beck, Great Fryup Beck and Glaisdale Beck.

(b) Many of the channels draining the Esk are incised with limited floodplain development. There is thereby limited opportunity for the storage of fine sediments on the adjacent floodplains. However, the shallow gradient of the Esk downstream of Glaisdale may provide the opportunity for the storage of the coarser fraction of fine sediments.

(c) The lack of a negative relationship between area and SSY is indicative of a system whereby there may be a steady supply of material, possibly from in-stream sources and sources proximal to the channel.

5.2.2 Temporal Variability in the Pattern of Suspended Sediment Flux

Section (5.2.1) highlighted the annual total sediment loadings across the catchment and how these vary as a function of catchment area. Given the varied hydrological conditions between monitoring periods (Chapter 6), there is considerable variability in suspended sediment fluxes over time. Figure 5.8a shows the quantity of fine sediment transferred (t day^{-1} due to the sampling intervals between periods varying by ± 10 days). In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a '+'. Figure 5.8 b provides information on the spread of sediment flux across the Esk catchment during the sampling period through the use of the coefficient of variation (CV %) for each time-period.

The period of highest sediment flux across the Esk catchment is between 30th August and 28th September 2008 with a median value of 2.50 t day^{-1}. In terms of actual flux, there is a great deal of between site variability at this time period with an inter quartile range of 0.84 – 7.46 t day^{-1}. However, the relatively small CV of 89.2% highlights that during this period, the variability is small relative to the mean load transferred with sediment transfer being relatively extensive throughout the Esk catchment. The period of next highest flux is the monitoring period immediately prior to the period of maximum flux (between 3rd and 30th August 2008) with a median value of 2.16 t day^{-1} with an inter quartile range of 0.90 – 10.18 t day^{-1} (Figure 5.8 a). This sampling period produces the highest inter quartile range in flux however; the CV is a moderate 109% (Figure 5.8 b). There are many periods of relatively low sediment flux throughout the sampling period. However, the lowest is observed between 24th October and 16th November 2007, with a median flux of 0.14 t day^{-1} and inter quartile range of 0.06 – 0.36 t day^{-1} (Figure 5.8 a). The period spanning 30th January – 6th March 2009 represents the largest CV of 174% (Figure 5.8 b). This is despite a moderate median flux of 1.06 t day^{-1}. However, the large fluxes observed at the Esk at 6 Arch Bridge and Esk at Glaisdale (18.83 and 9.87 t day^{-1} respectively) act to enhance the CV over this sampling period. This demonstrates that sediment fluxes can vary appreciably over the course of a year, with a considerable amount of variation occurring between sites during individual sampling periods as highlighted by the CV % plot.

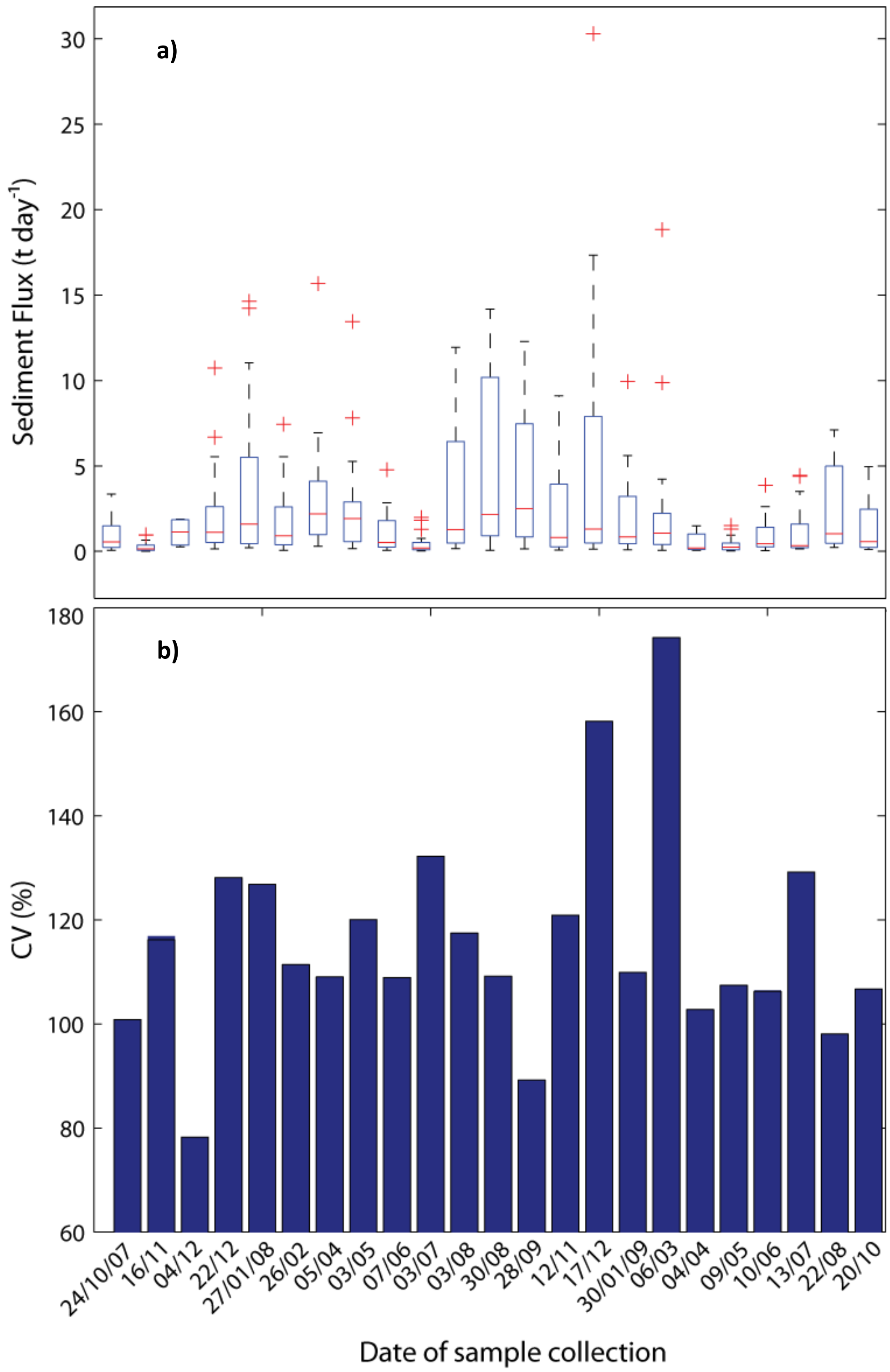


Figure 5.8: a) Monthly sediment fluxes (t day^{-1}) and; **b)** Coefficient of Variation (CV %) collected by TIMs across the Esk catchment

5.2.3 Spatial Patterns in Suspended Sediment Particle Size Characteristics

This section presents results of the spatial variability in suspended sediment particle sizes transported through the Esk catchment. The particle size of suspended sediment is a key control of entrainment, deposition and storage dynamics. An understanding of the particle sizes therefore provides insight into the erosion and transport processes in operation through a catchment.

The particle size of suspended sediment varies across the Esk catchment (Figure 5.9) and although the absolute range of d_{50} measurements is a considerable 4.0 – 496.3µm, the range in median d_{50} values for individual monitoring sites spans 9.6 – 30.1µm. The largest median d_{50} particle size (30.1µm) of suspended sediment is found in the headwaters of the river Esk at Westerdale. This site also has a considerable range in d_{50} distributions through time, ranging from 11.7 – 164.1µm with an interquartile range spanning 20.7 – 63.3µm, highlighting that the vast majority of transfer is of the silt fraction although sand may dominate certain sampling periods. Following the Mann–Whitney–Wilcoxon U test, it has been identified that the median particle size measured at this headwater reach is statistically different ($P < 0.05$) from all monitoring locations in the Esk catchment with the exception of Stonegate Beck, Hob Hole and the Esk at Danby which all have large d_{50} values of 21.0, 28.4 and 22.0µm respectively. These sites represent the areas of the catchment where the coarsest fine sediment is transferred.

These areas of relatively coarse sediment transfer are distributed throughout the Esk catchment, with Hob Hole and the Esk at Westerdale draining the South-Western extent of the catchment in the NYMNP. Conversely, Stonegate Beck drains the northern area of the central valley whereas the Esk at Danby is an area of the catchment which has been highlighted as possible significant source in the Esk valley, with tall, unconsolidated, sandy banks dominating this section of the main Esk river. These sub-catchments represent some of the steepest areas within the catchment. However, within a national context, these areas of relatively coarse suspended sediment transfer are not remarkable and compare favourably with other studies which show silt and clay sized material (< 63µm) being the predominant size fractions being mobilised (Walling and Moorehead, 1989; Walling et al., 2000).

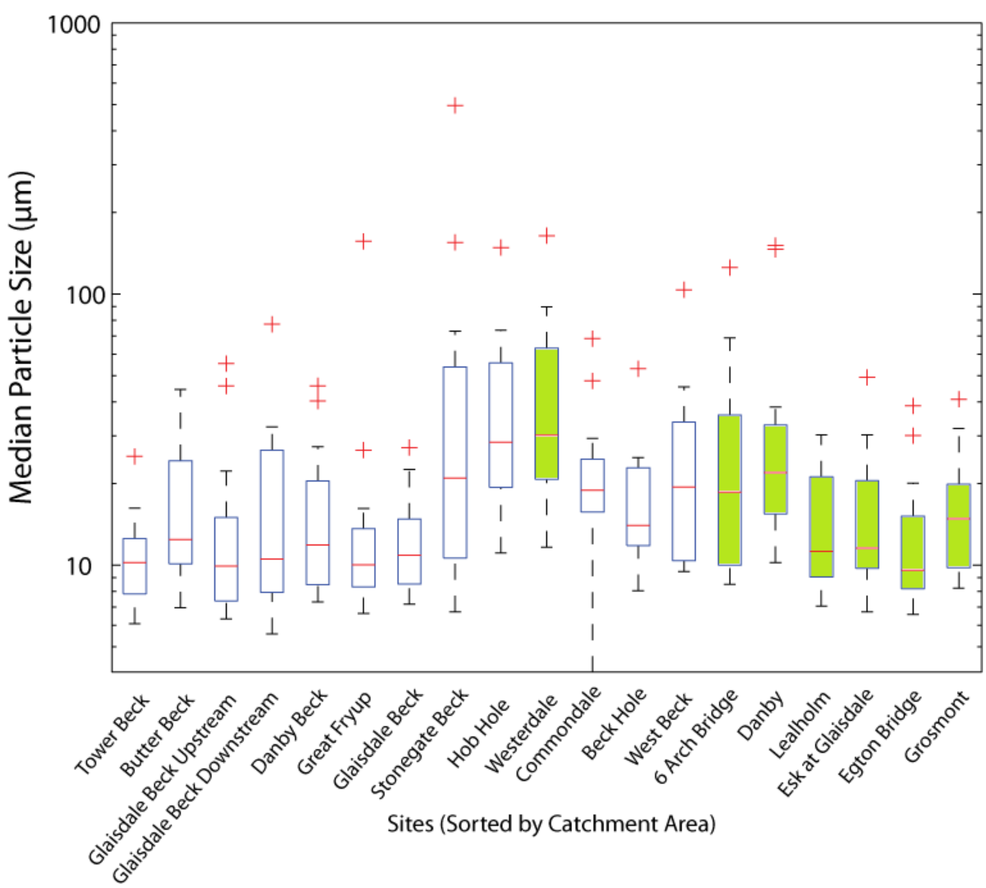


Figure 5.9: Box plot highlighting the spatial variability of median particle sizes (µm) between collection periods. Sites on the main Esk River are coloured green. Note log scale on y-axis.

Downstream of the main Esk at Danby, the median particle size drops to 11.2µm at Lealholm, which then remains relatively consistent, varying between 9.6 – 14.8µm down to the Esk at Grosmont (lowest monitoring point). The median value of 9.6µm measured at Egton Bridge is the smallest observed, highlighting the progressive winnowing of the coarsest material out of suspension and into storage as distance increases downstream from the steep headwater tributaries (or through the dissintegration of aggregates). This progressive reduction in the d_{50} of suspended sediment is not remarkable given that with increasing distance downstream a longitudinal reduction in slope and current shear velocity would be found (Davide et al., 2003), creating opportunities for within-channel storage and the selective deposition of coarser particles. A Wilcoxon-Mann-Whitney non-parametric test was conducted to test for significant differences between the median particle size's at each of the monitoring sites in the Esk catchment (Figure 5.10).

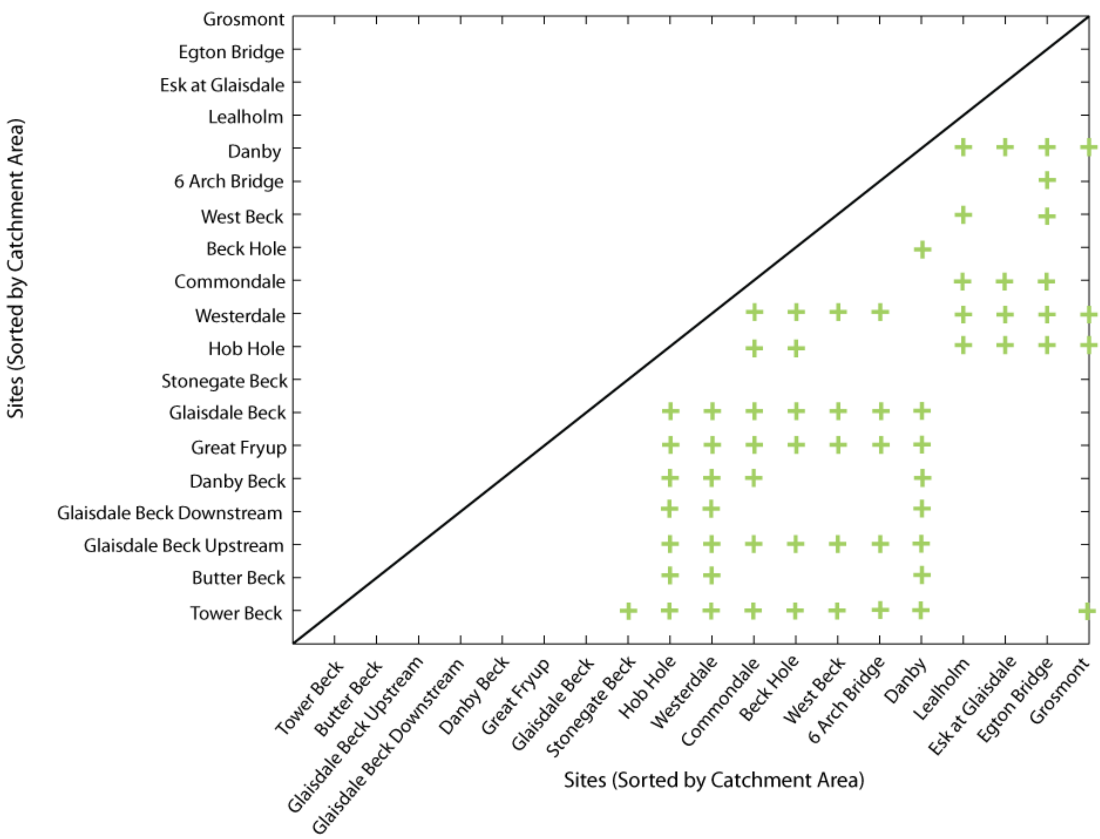


Figure 5.10: A summary of the statistically significant differences (P < 0.05) in median particle size (µm) at TIMs monitoring locations in the Esk catchment. The presence of a '+' illustrates significant differences between the two groups.

5.2.4 Temporal Variability in the Pattern of Suspended Sediment Particle Size

As has been observed with the flux of fine sediment through time in the Esk catchment (Section 5.2.3), the particle size characteristics also vary considerably throughout the monitoring period. In much the same way as flux, the particle sizes are controlled by sediment availability, thresholds of entrainment and the presence of areas within the catchment for deposition to occur. Figure 5.11 shows an annual pattern in the variation of SS median particle size, with the median diameter increasing from September 07 through to the end of January 08 with a peak of 23.5µm at 27th January 08. This coincides with a period of relatively high sediment flux and water yield throughout the catchment (Figure 5.8). Unfortunately, there is a period of missing data between 27th January – 3rd May 08. Between 3rd May and 7th June, the median particle size is only 11.9µm which declines further to 9.9µm between 7th June and 3rd July. This represents a period of low flux with a high relative CV, highlighting the disparity in transfer across the catchment. The median particle sizes across the catchment then begin to increase up to their peak of 25.4µm in the 30th January 2009 sample collection. The timing of this peak in coincides with that of the first hydrological year, and has a similar median sediment size (25.4 cf. 23.5µm). The moderate CV values during this period also indicates that the pattern of consistently increasing particle diameter is generally replicated across the Esk catchment. These data suggest that following a period of relatively minimal sediment transfer, the subsequent period of elevated flux is accompanied by an increase in the particle sizes transferred. Following this peak in median diameters, particle sizes then continually fall in the period spanning 30th January 2009 – 9th May 09 when the minimum d_{50} value of 8.4µm is found. During this period of falling median particle sizes, the suspended sediment flux and water yield across the Esk is also low.

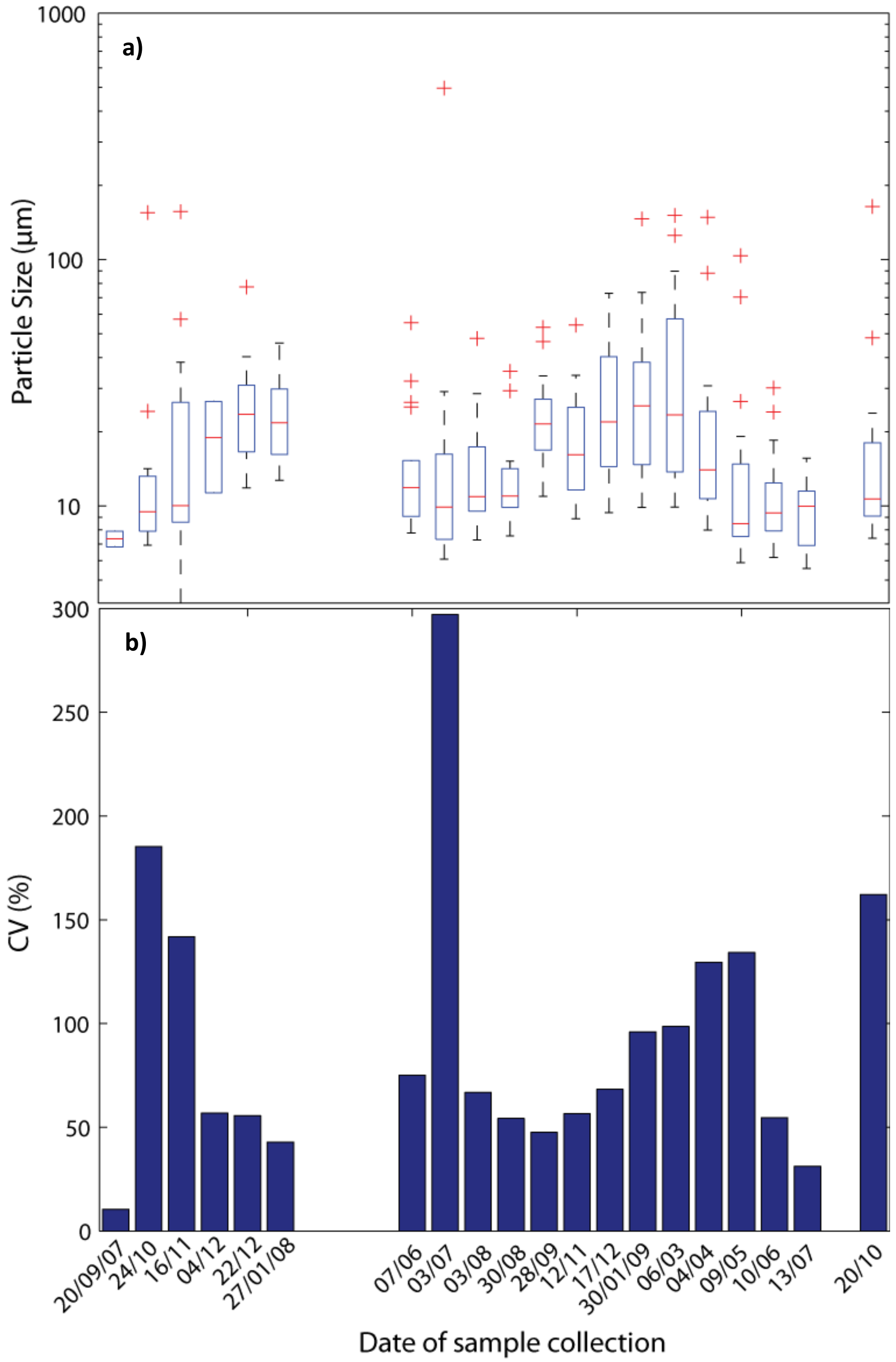


Figure 5.11: a) Monthly median particle sizes (µm) and; **b)** Coefficient of Variation (CV %) collected by TIMs across the Esk catchment. Note log scale on y-axis of particle size (µm).

These findings that the minimum d_{50} values occur during the summer months contrasts with the findings of Stone & Walling (1997) who observed statistically significant differences between the median particle sizes transported in autumn/winter compared to those of spring/summer, with the coarser fraction occurring in the spring/summer months. It could be hypothesised that this is related to flow. However, Stone & Walling (1997) also observed an inverse relationship between flow and size of sediment transported indicating supply and access to sediment stores being a dominant control. Analysis of median d_{50} values for the Esk catchment as a function of river flow (Figure 5.12) provides evidence that this may not be the case for the Esk catchment. A strong positive linear relationship between flow and the size of fine suspended sediment being transferred is observed. This finding conforms to the traditional assumption that increases in flow facilitate the transport of larger particles thereby producing a positive relationship between discharge and the magnitude of the coarse fraction (Horowitz, 1991). However, this finding is contrary to those reported by Slattery & Burt (1997) where complex dynamics of sediment delivery and availability result in deviations from this function.

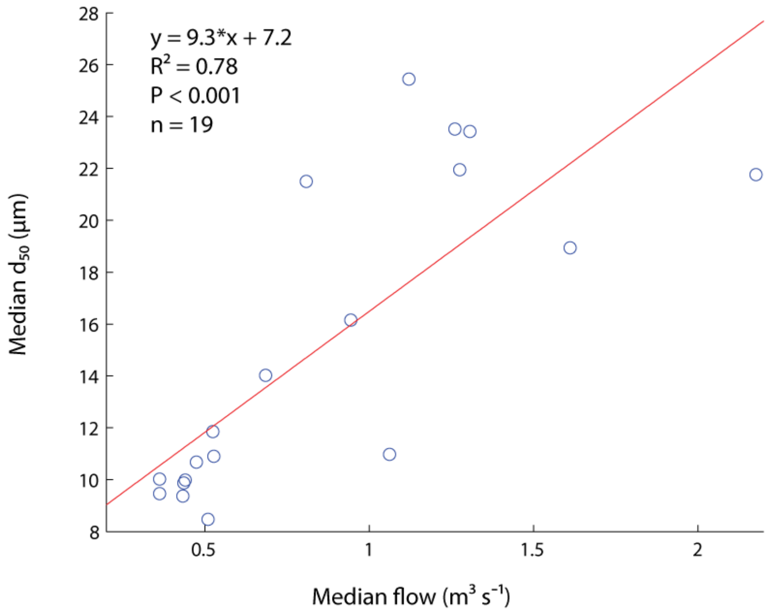


Figure 5.12: Relationship between the median discharge recorded at Danby and the across catchment median d_{50} value over the entire monitoring period

5.2.5 Spatial Patterns in the Organic Content of Suspended Sediment

Information on the organic component of the suspended sediment being transported through the Esk catchment is required to provide information on the organic/mineral composition. Although the inorganic component typically dominates in terms of transported mass, organic sediment can have important on the conveyance of pollutants and contaminants and affect the productivity of biological communities (cf. Chapter 2).

The mean organic content across all sites over this monitoring period was 13.0% (CV = 37.0%). The minimum organic content was 1.12%, which was found at the Esk at Lealholm monitoring station, whereas the greatest proportion of organic material was 32.2% at Danby Beck. Although this is a considerable range between the minimum and maximum values, 266 of the 374 measurements undertaken (71.1%) fall between 10 and 30% (Figure 6.9) which Walling & Webb (1987) suggested to be typical of British rivers. Only two measurements exceeded 30%. These were obtained from Danby Beck and West Beck, whereas 106 samples were below the 10% threshold (Figure 5.13). These samples were obtained from all locations with the exception of Tower Beck and West Beck which have minimum values of 11.6 % and 11.2% respectively (Figure 5.14).

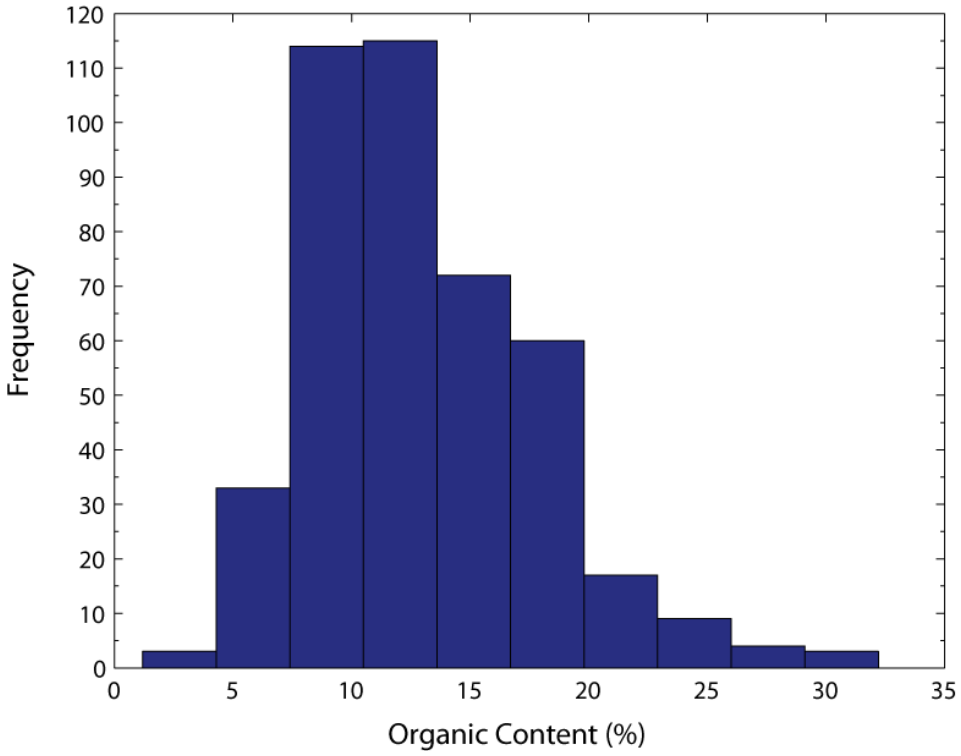


Figure 5.13: Histogram of measured organic content from sites across the Esk catchment

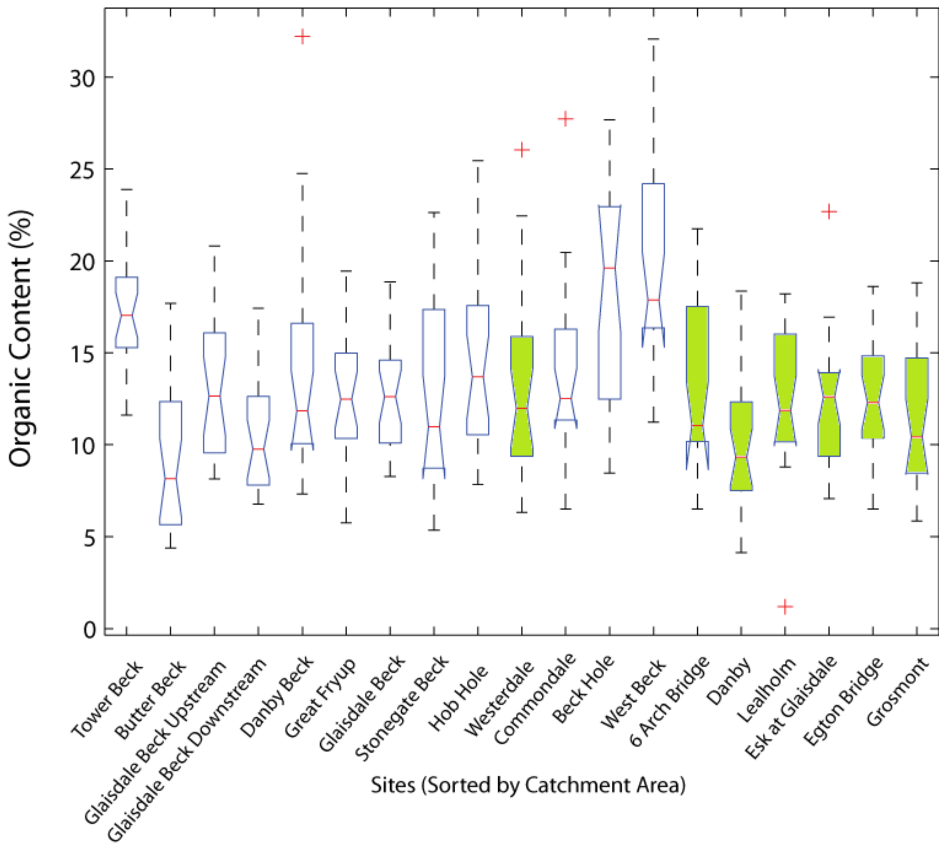


Figure 5.14: Box plots highlighting the spatial variability of organic content (%) between TIMs collection periods. Sites on the main Esk River are coloured green.

Throughout the monitoring period there is a great deal of within-site variability in the organic fraction of fine sediment, with a typical range in values of ~20%. Therefore, it is somewhat difficult to visually differentiate between the sites. However, by conducting a Wilcoxon-Mann-Whitney non-parametric test it has been found that statistically significant differences in the median site values do exist. Figure 5.15 illustrates that individual sites, namely Beck Hole, West Beck, Butter Beck, Tower Beck and the Esk at Danby have median organic content values that are significantly different from at least 50% of the other monitoring sites in the catchment.

More specifically, Beck Hole was found to have the highest median value of 19.6% and is significantly different ($P < 0.05$) from all other monitoring location in the Esk with the exception of Tower Beck, Commondale Beck and West Beck. Similar to Beck Hole, West Beck is also located in the Murk Esk catchment. This site has a median organic content (%) value of 17.9% which is significantly different from all other sites with the exception Tower Beck and West Beck. Tower Beck also has a high median organic content of 17.0%, which makes it statistically similar to the Beck Hole and West Beck Sites. However, it is statistically different from all other sites.

Butter Beck has the smallest median organic content value (8.16%), which results in significant difference between this site and all other locations with the exception of Glaisdale (downstream), Stonegate Beck and the Esk at Danby, which all have similarly low median organic contents of 6.76%, 10.98% and 9.32% respectively. Unlike Butter Beck, the median organic content measured at Stonegate Beck is statistically similar to the vast majority of sites with the exception of Tower Beck, Beck Hole and West Beck.

In summary, these findings illustrate significant differences in the median organic content of the Murk Esk catchment and all sampling sites along the main Esk River including tributaries with the exception of Tower Beck and Commondale Beck. These two headwater tributaries of the upper Esk valley transfer fine sediment with the highest organic content. Conversely, the organic content of transported sediment transferred through the majority of the Esk valley is statistically similar, with few individual sites having different median values.

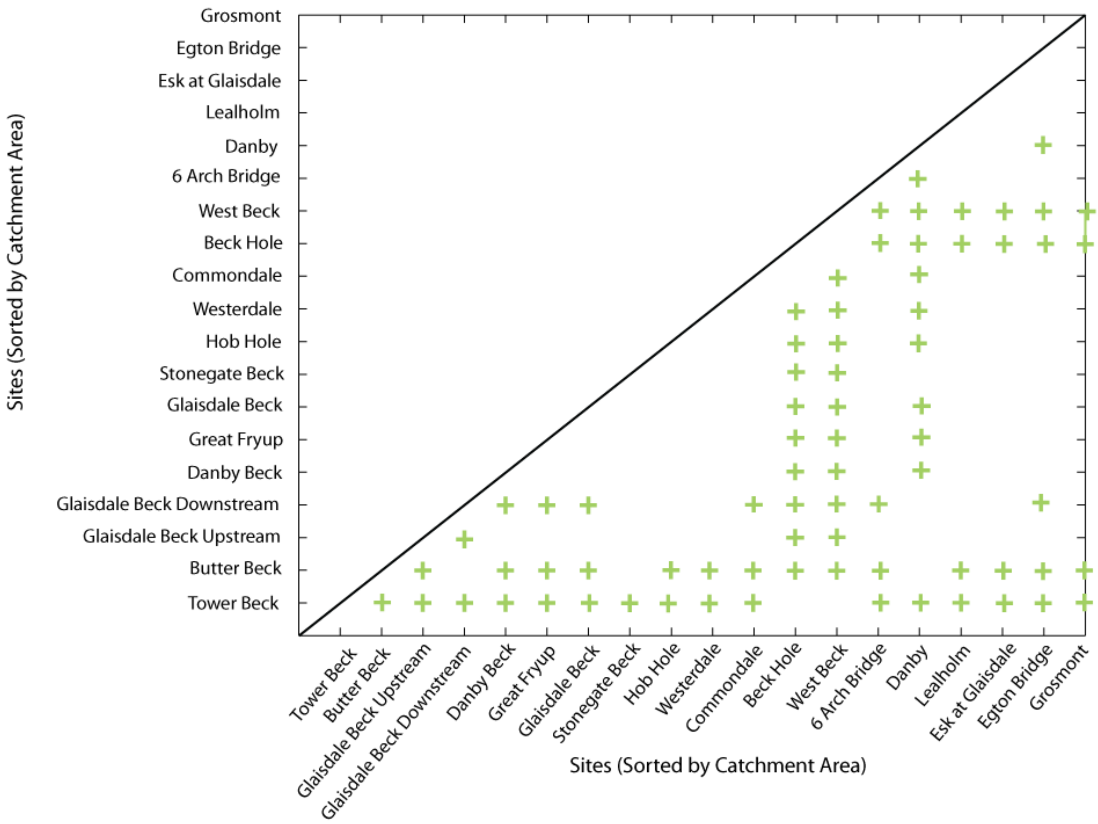


Figure 5.15: A summary of the statistically significant differences ($P < 0.05$) in organic content (%) at TIMs monitoring locations in the Esk catchment. The presence of a '+' illustrates significant differences between the two groups.

With reference to the relatively high organic contents measured in the Murk Esk catchment, a logical explanation for this may be the enhanced transfer of litter from the riparian zone (cf. Madej, 2005) in these catchments which are primarily overlain by shrub heath (74% and 41% respectively) and to a lesser extent coniferous forest.

Conversely, Butter Beck which has a low proportion of POM relative to the inorganic fraction has been the focus of management activity in the last 10 years, with woody debris being removed from the channel. This woody debris, which is rarely mobilised by flows may not have provided much to the POM content of the river due to its slow breakdown rates (Webster et al., 1999). However, these natural structures which provide stability and act to diversify flow may enhanced the retention of POM (cf. Bilby, 1981; Naiman, 1982) and produced a rich faunal habitat with a rich diversity of flora. With the removal of this material, it is feasible that in-stream production of organic matter has subsequently declined. The combination of these processes may have therefore acted to produce the relatively low POM content of the fine suspended sediment in this sub-catchment.

The broad scale POM dynamics observed in this research catchment are comparable with those found elsewhere, with most material being produced and transferred in 1st – 3rd order streams (Naiman et al., 1987; Minshall et al., 1983; Vannote et al., 1980). However, there appears to be limited evidence of the systematic organisation of POM content with increasing distance downstream of the headwaters (cf. Richardson et al., 2005), rather internal controls of land use and anthropogenic activity dominates the in-stream signal that is observed.

5.2.6 Temporal Variability in Patterns of Organic Content in Suspended Sediment

The considerable range in organic content (%) observed between sites (Section 5.2.5) is also apparent in variations in organic content on a monthly basis. For example, the smallest range in data spans from 6.2 – 12.6%, which was collected on 3rd May 2008 whereas the largest range spans from 7.5 – 32.2%, which was collected on 13th July 2009. Despite this considerable range between the minimum and maximum values, the inter-quartile range is relatively constant throughout the monitoring period thereby allowing seasonal trends in organic content to be identified (Figure 5.16).

The highest median organic content occurs at the start of the monitoring period on 24th October 2007 (18.2%). Organic content then falls to a minimum value in the first year of 9.4% on 27th January 2008. The proportion remains low for the succeeding period up to 3rd May 08. Over this time of this year, the CV is relatively low indicating a relatively consistent response across the catchment. The organic contribution then begins to increase in the sampling period ending on the 7th June, where a median value of 14.9% is reached. This upward trend is continued through to the 3rd August where a median value of 17.7% is reached. A second decline in the organic proportion occurs through to the minimum value of 8.8% at the sampling period ending 6th March 09. A second upward trend is then exhibited through to the peak value of 18.2% at 13th July 09 before once more falling.

The pattern clearly illustrates seasonality in both monitored hydrological years, with the peak in organic content occurs in the summer months (3rd July – 3rd August in year one and 10th June – 13th July in year two). This is consistent with research by Ankers *et al.* (2003) who found that organic (matter) carbon peaked during summer and early autumn months. This temporal cycling may be due to the production of autochthonous material from phytoplankton production (cf. Hedges et al., 2000), or potentially from allochthonous sources such as litter inputs corresponding to maximum vegetative growth (Wetzel et al., 1977).

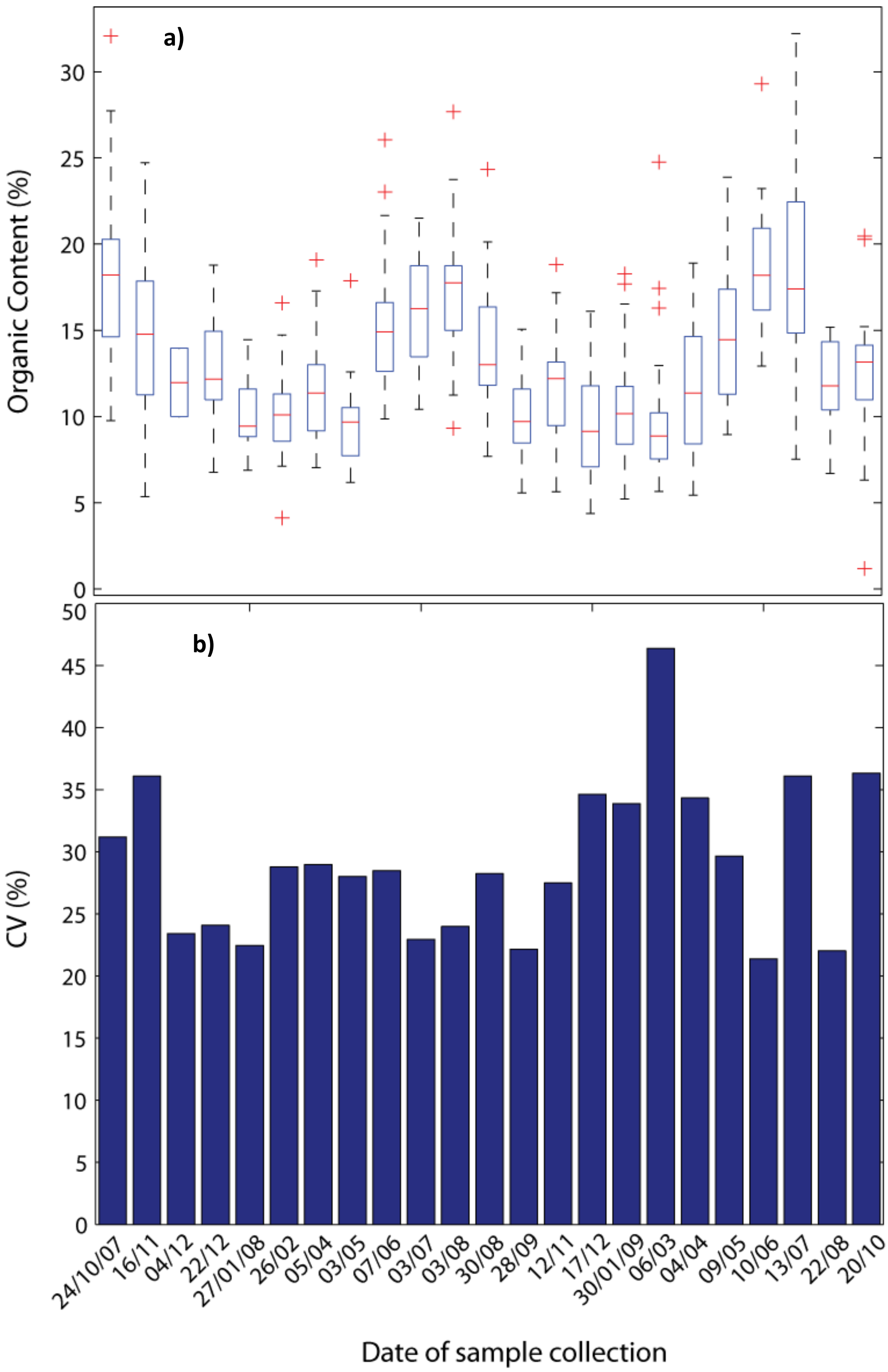


Figure 5.16: a) Monthly median organic content (%) and; **b)** Coefficient of Variation (CV %) collected by TIMs across the Esk catchment

5.2.7 Section Summary

This section has demonstrated how the quantity and physical properties of suspended sediment vary spatially and temporally at TIMs monitoring locations distributed throughout the Esk catchment. This analysis has found that:

(1) Along the main Esk River, the suspended sediment loads (t) generally increase with catchment area. The magnitude of increase is well scaled with catchment contributing area resulting in a fairly consistent SSY-A relationship, indicative of a system where hillslope contributions are not dominant. It may be that sources from within (and proximal) to the channel dominate or that inputs from tributaries in the lower reaches are important.

(2) In the tributaries of the River Esk, peak SSYs occur in the sub-catchments in the central Esk valley such as Butter Beck, Glaisdale Beck and Great Fryup Beck. Smallest SSYs are measured in the tributaries draining the headwater catchments to the west of the catchment such as Tower Beck and Baysdale Beck (Hob Hole).

(3) Sediment flux varies appreciably over the course of a year, with a considerable variation occurring between sites during individual sampling periods.

(4) Areas of relatively coarse suspended sediment are distributed throughout the Esk catchment at Baysdale Beck (Hob Hole), the Esk at Westerdale, Stonegate Beck and the Esk at Danby. These sub-catchments represent some of the steepest areas within the catchment.

(5) Median absolute particle sizes of the suspended sediment compare favourably with other studies which show silt and clay sized material (< 63µm) are the predominant size fractions transferred.

(6) The median particle size of transported SS exhibits a strong positive relationship with river flow. Increases in flow facilitate the transport of larger particles.

(7) The organic content (%) of SS through the majority of the Esk valley is similar, with few individual sites being significantly differences. There is limited evidence of the systematic organisation of POM content with increasing distance downstream of the headwaters. Internal controls of land use and anthropogenic activity dominates the observed in-stream signal.

(8) There is clear evidence of seasonality in the proportion of organic content transported with the maximum occurring during the summer months.

5.3 Upper Derwent Catchment

Monitoring of the properties and mass of fine suspended sediment flux across the Upper Derwent catchment began on 22nd July 2008 and continued through to 20th October 2009. Akin to the Esk catchment, the TIMs sampling framework in the Upper Derwent catchment was designed to capture the broad spatial patterns of sediment transfer across the catchment (Figure 5.17). The adopted sampling design is schematically represented in Figure 5.18. Given the number of tributaries of the River Rye, complete spatial representation was unfeasible. In the upland areas of the catchment (as low as Church Bridge) all of the major tributaries were sampled as close to the confluence with the River Rye as logistically possible. The sampling point furthest from the source on the River Rye is West Ness. It was not possible to sample further downstream of this point due to the channel depth. Additional tributaries which join the Rye downstream of this point are however sampled to ensure a good spatial representation across the Upper Derwent catchment.

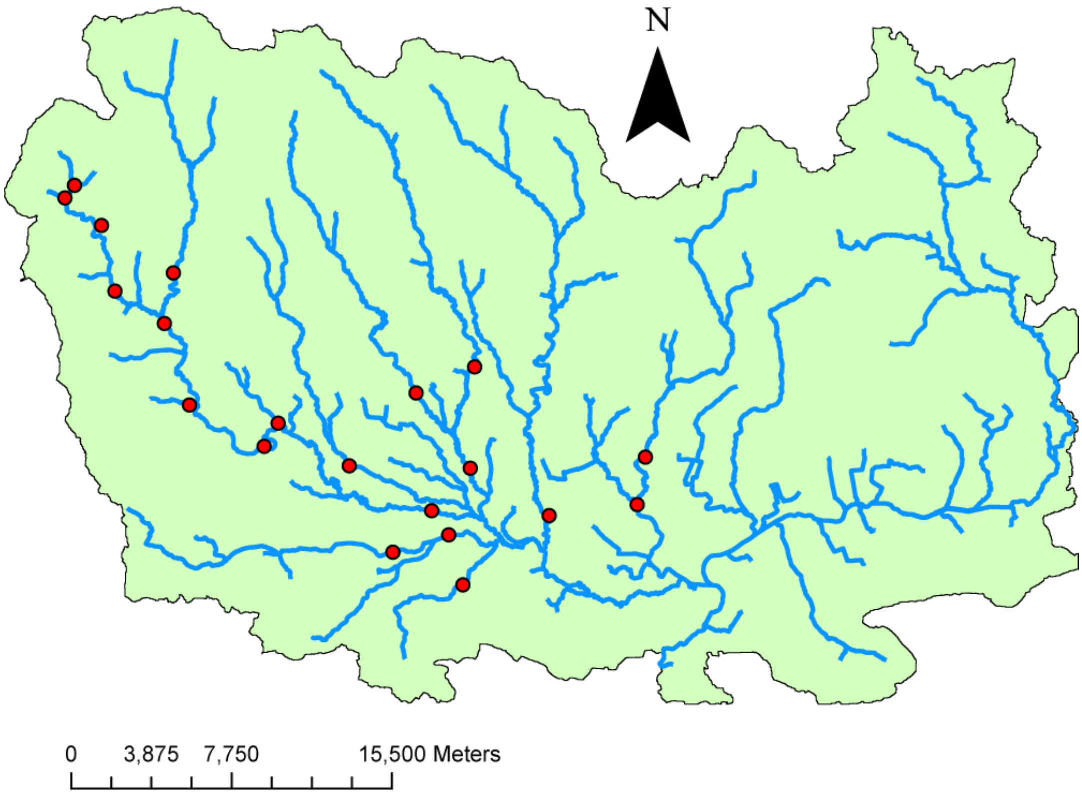


Figure 5.17: Location map of the TIMs sites in the Upper Derwent catchment. Red dots represent TIMS monitoring sites

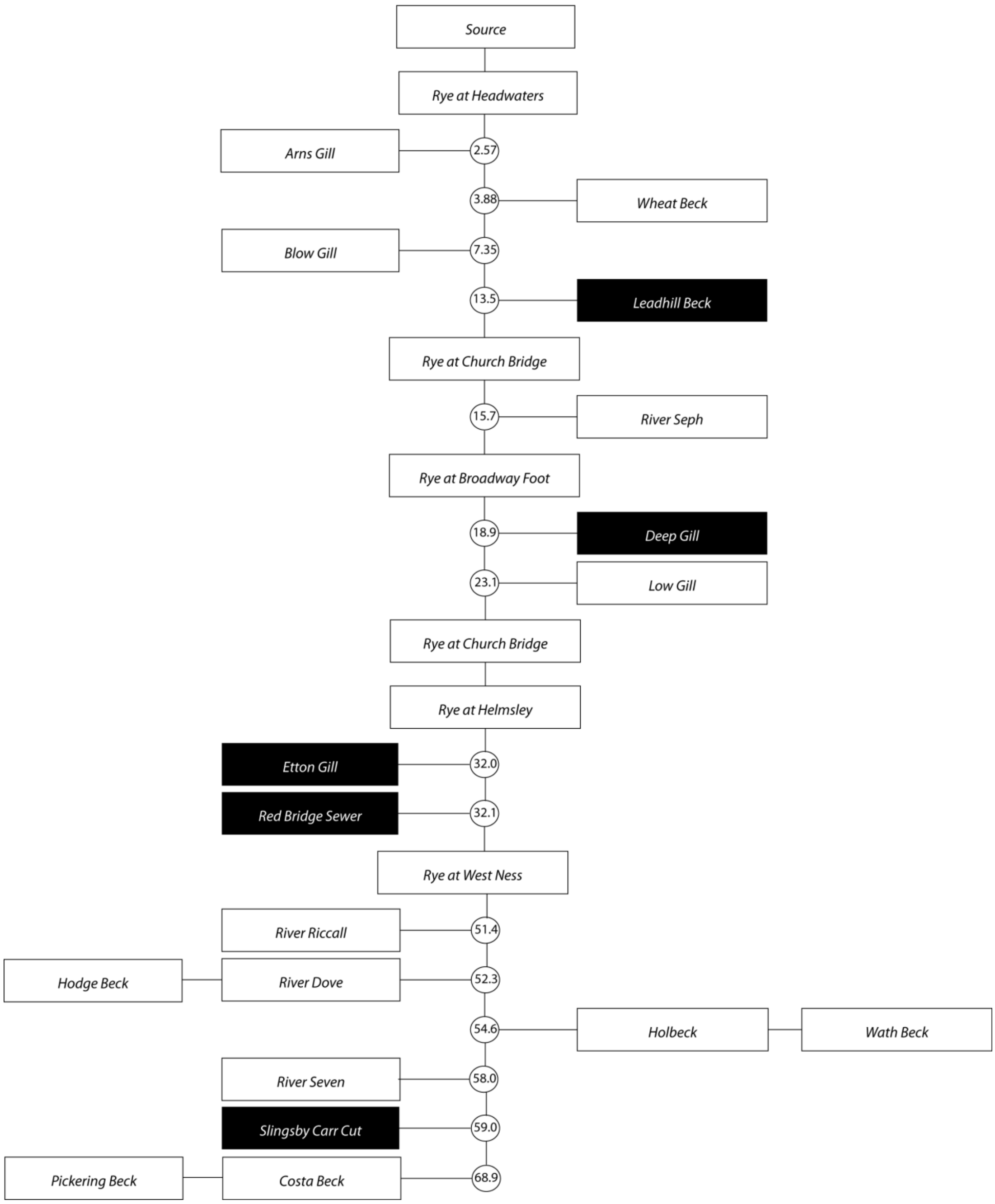


Figure 5.18: Schematic diagram of TIMs monitoring locations along the main Rye River and tributaries. Numbers in circles represent the distance (in km) from the river source

5.3.1 Spatial Variability in the Mass of Suspended Sediment Transfer

Patterns of suspended sediment flux are presented in terms of relative load (t) and specific yields (t km^{-2}) in the catchment. Specific sediment yield (t km^{-2}) is assessed with relation to the catchment contributing area. Figure 5.19 a shows the between site variability of the between site loads over the course of the 2008/09 hydrological year. This broadly indicates that as catchment contributing area increases, the annual suspended sediment load also increases. The minimum annual load was measured at Wheat Beck (23.5 t), whereas the maximum load was obtained at the Rye at West Ness (1788.3 t). The mean loading is 564.9t with a CV of 88.3%.

When suspended sediment loads are calculated to represent the area-specific sediment yield (t km^{-2}); greater differences between the areas of sediment transfer can be seen (Figure 6.13 b). The minimum SSY is observed at Pickering Beck (2.4 t km^{-2}), which drains a 68.25km^2 catchment to the East of the catchment which is dominated by cereals and improved grassland, typical of these piedmont areas. Conversely, the maximum SSY was observed at Hodge Beck (23.8 t km^{-2}), a 48.4km^2 catchment draining the central northern area of the catchment.

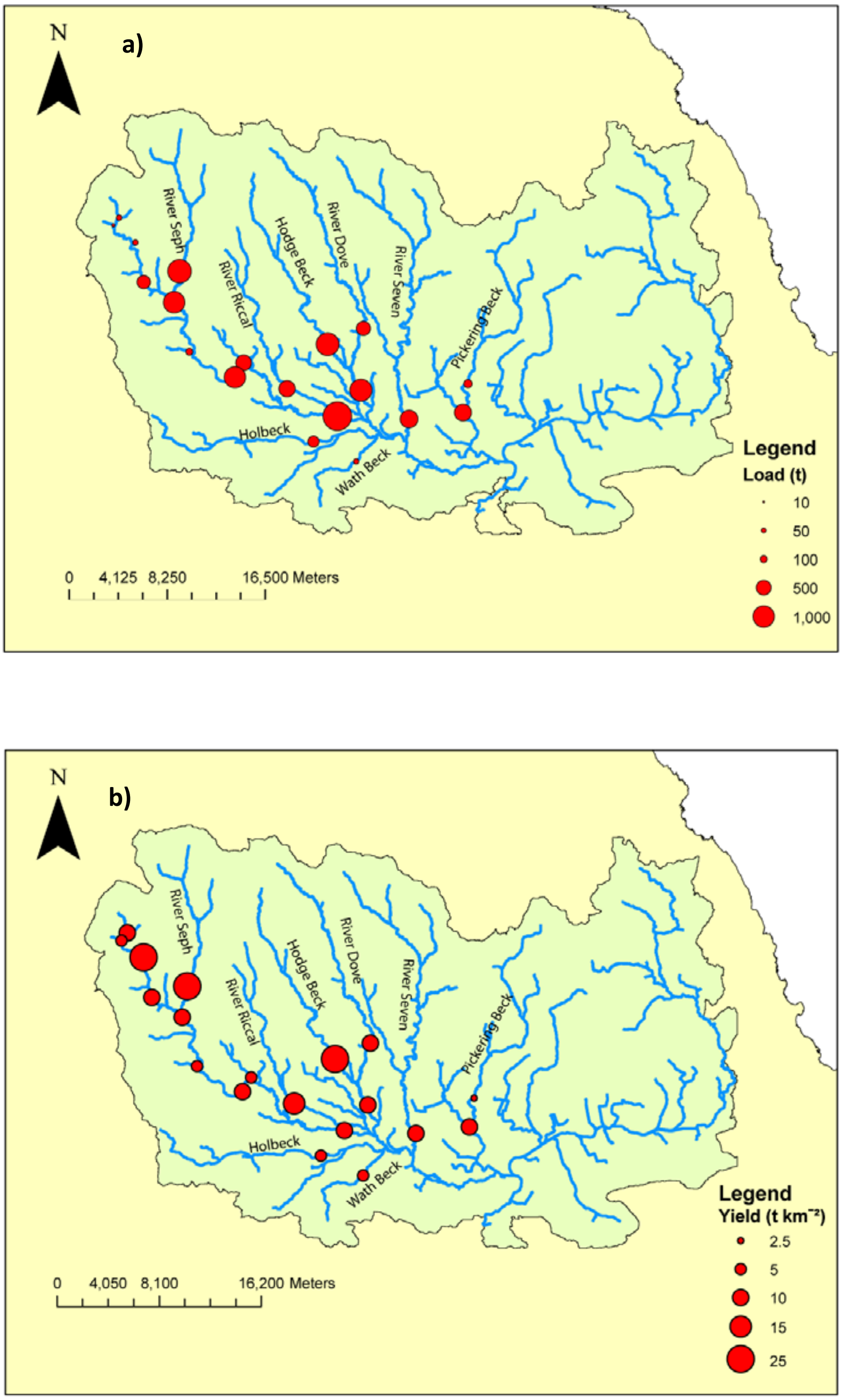


Figure 5.19: Mass of fine suspended sediment transferred through the river networks of the Upper Derwent during the 2008/09 hydrological year represented as **a)** loads (t) and; **b)** specific yields (t km^{-2})

From Figure 5.19 b it is also clear that the sub-catchments of Hodge Beck, River Seph, Blow Gill and the River Riccal generate more suspended sediment per-unit area than many of the higher-order streams and sites along the main Rye River. These catchments produce SSYs of 23.8, 18.8, 15.3 and 14.7 t km^{-2} respectively. The spatial patterns of SSYs across the catchment appear to be as follows:

(1) The very headwater tributaries of the Upper Derwent catchment of Wheat Beck, Arns Gill and Rye at Headwaters have moderate and low specific yields ranging from 4.0 – 9.2 t km^{-2} whereas Blow Gill produces one of the largest SSYs in the catchment.

(2) There is relatively little variability in SSYs with increasing catchment size along the main Rye River, with yields ranging from a minimum of 2.6 t km^2 at Helmsley to the maximum of 7.67 t km^{-2} at West Beck.

(3) There is a great deal of variability between sub-catchment SSYs (Figure 5.19 b). However, it does appear that sub-catchments draining the south of the River Rye produce relatively low SSYs (e.g. 3.3 and 4.7 t km^{-2} for Wath Beck and Holbeck respectively), compared to the northern catchments which drain the south of the North York Moors and account for three of the four largest SSYs in the catchment.

When the area-specific sediment yields are plotted against catchment area, a great deal of sub-catchment variation can be observed with SSYs fluctuating markedly over a small range in catchment areas (Figure 5.20). Initially, SSY decreases from 15.3 t km^{-2} to 3.3 t km^{-2} within the catchment area range of 4.6 km^2 - 22.2km^2. SSYs then generally increases from 3.26 t km^{-2} to 23.77 t km^{-2} within the catchment area range of 22.2 – 48.4km^2. SSY then once again generally decreases to 4.7 t km^{-2} at 57.9 km^2. Following this point, SSY is generally relatively stable with increasing catchment size up to 236.33km^2 on the Rye at West Ness.

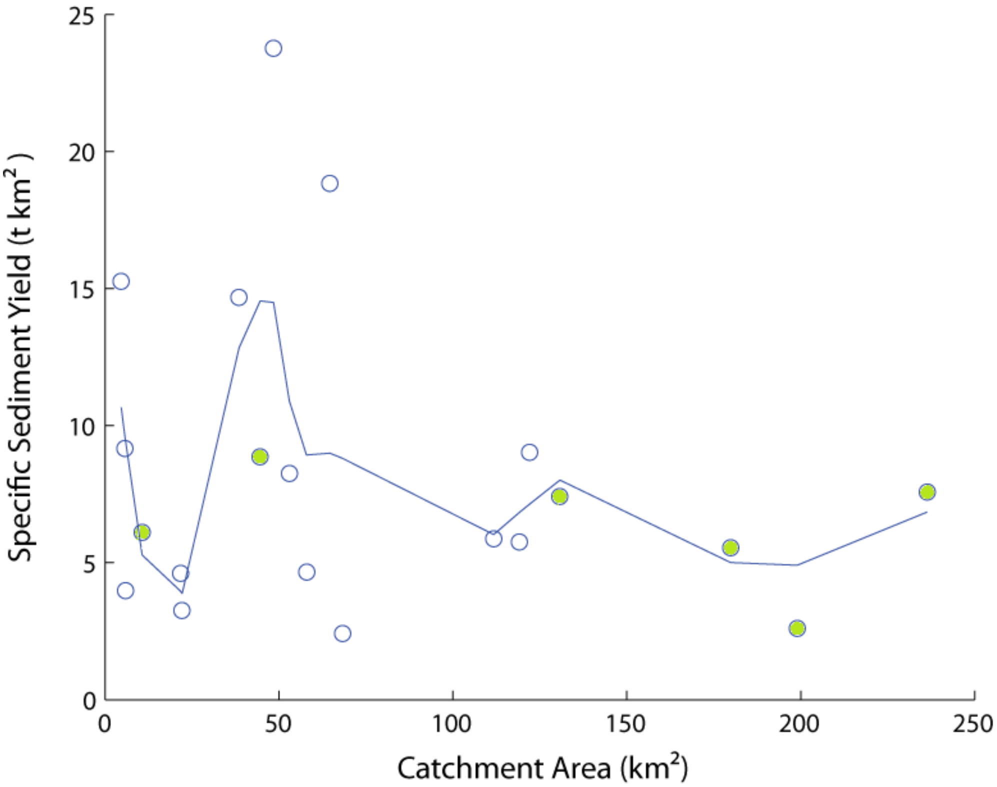


Figure 5.20: Scatter plot of contributing catchment area vs. specific sediment yield (SSY) in the Upper Derwent catchment with a superimposed LOWESS smoothing fit for the 2008/09 hydrological year. Sites on the main Rye River are coloured green.

5.3.2 Temporal Variability in Patterns of Suspended Sediment Flux

Given the varied hydrological conditions between monitoring periods (cf. Chapter 6); there is considerable temporal variability in suspended sediment loadings. This is illustrated by the box plots shown in Figure 5.21. The quantity of fine sediment transferred is represented in t day^{-1} due to the sampling intervals between periods varying by ± 10 days. The period of highest sediment flux across the Upper catchment is between 27th June and 4th August 2009 with a median value of 2.4 t day^{-1}. There is a great deal of between site variability at this time period with an inter quartile range of 0.3 – 6.5 t day^{-1}. This sampling period produces the highest inter quartile range in flux estimates which is indicative of relatively large spatial variability across the catchment compared to previous periods. This is further exemplified by the high CV of 83.9%. The period of next highest flux is the monitoring period between 7th January and 11th February with a median value of 1.8 t day^{-1} with an inter quartile range of 0.3 – 3.0 t day^{-1}. This demonstrates that sediment flux's can vary appreciably with a considerable amount of variation occurring between sites during individual sampling periods, whereas between the sampling periods the sediment flux is fairly consistent with a lack of seasonal patterns and the presence of consistent broad scale patterns.

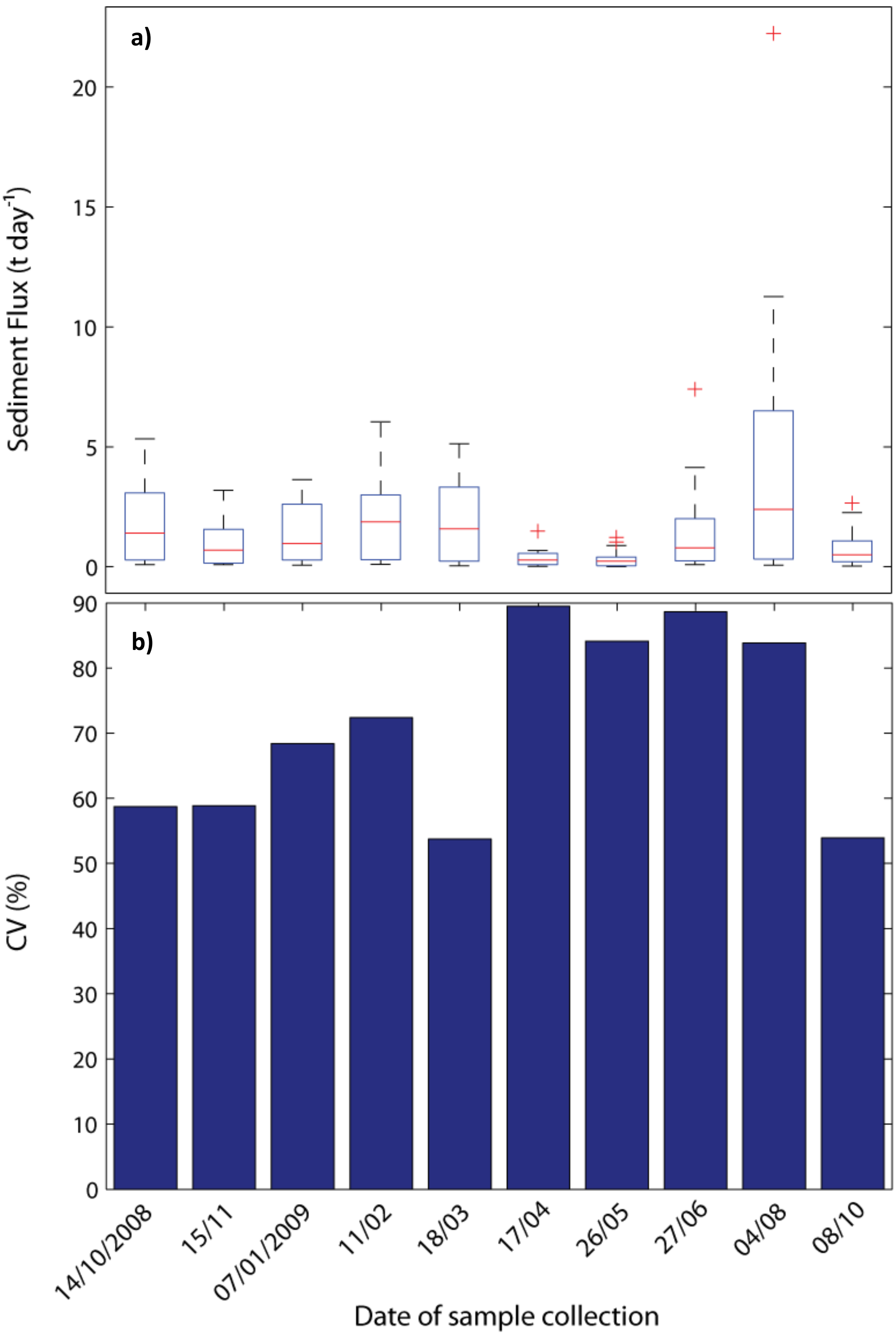


Figure 5.21: a) Monthly sediment fluxes (t day^{-1}) and; **b)** Coefficient of Variation (CV %) collected by TIMs across the Upper Derwent catchment

5.3.3 Spatial Patterns in Particle Size Characteristics of the Suspended Sediment

The particle size of suspended sediment varies across the Upper Derwent catchment (Figure 5.22). The distributions of suspended sediment particle sizes across the Upper Derwent catchment is extremely varied. The median d_{50} range spans 7.4 – 138.7µm. The largest median d_{50} particle size (138.7µm) of suspended sediment is found in the smallest catchment of Blow Gill, whereas the smallest median d_{50} particle size (7.4µm) is found in the Costa Beck catchment.

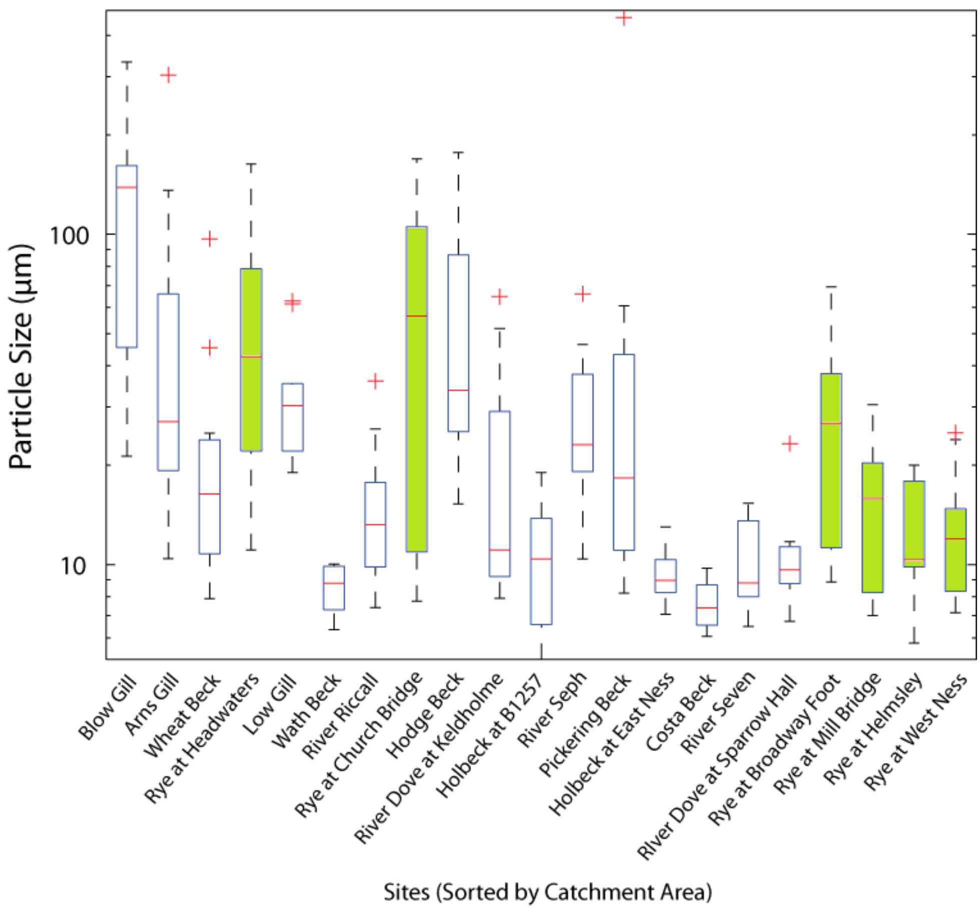


Figure 5.22: Box plot highlighting the spatial variability of median particle sizes (µm) between collection periods of approximately one month in the Upper Derwent catchment. Sites on the main Rye River are coloured green. Note log scale on y-axis.

Blow Gill (median d_{50} of 138.7 µm) has a considerable range in d_{50} distributions through time, ranging from 21.3 – 332.3 µm with an inter-quartile range of 45.4 - 161.2 µm. The median particle size measured at this headwater reach is statistically different from all monitoring locations in the Upper Derwent catchment with the exception sites at Headwaters and Church Bridge on the Rye and also Hodge Beck. The first two of these sites represent areas within the catchment which all have relatively large d_{50} values of 42.6 and 56.5 µm respectively, whereas the latter has a more moderate d_{50} of and 33.7µm but also has the largest range spanning 15.3 – 176.6 µm. These sites represent the areas of the catchment where the coarsest fine sediment is transferred.

Additionally, relatively coarse suspended sediment is also transferred at Arns Gill, which has a d_{50} value of 27.1 µm and a range in sediment size spanning 10.4 – 135.7µm. The data obtained from this site are statistically different from Blow Gill, Wath Beck, River Riccall, Dove at Keldholm, Holbeck at B1257, Holbeck at East Ness, Costa Beck, River Seven, Dove at Sparrow Hall and all river Rye stations downstream of Church Bridge. With the exception of Blow Gill, these sites represent the finest fraction of suspended sediment transferred in the Upper Derwent catchment with median particle sizes of 8.8µm, 13.2µm, 11.1µm, 10.4µm, 9.0µm, 7.4µm, 8.8µm, 9.6µm, 26.8µm, 15.9µm, 10.4µm and 12.0µm respectively.

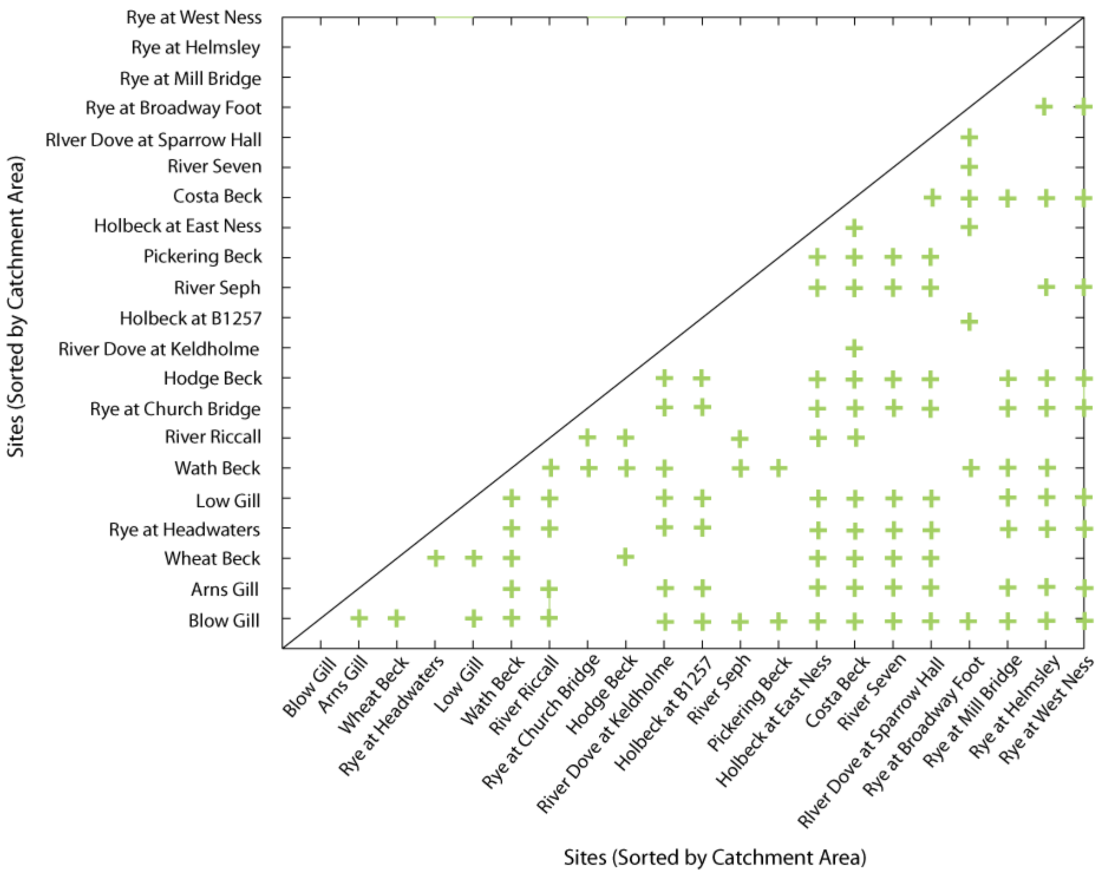


Figure 5.23: A summary of the statistically significant differences (P < 0.05) in median particle size (µm) at TIMs monitoring locations in the Upper Derwent catchment. The presence of a '+' illustrates significant differences between the two groups.

Overall, the data clearly show a marked difference between the upland and piedmont sediment transfer systems, with a a shift towards fine silt and clay materials dominating many of the incoming tributaries which drain the surrounding agricultural areas (Figure 5.24). Areas of relatively coarse fine sediment transfer are largely spatially restricted to the headwater sub-catchments of the Upper Derwent such as Blow Gill, Arns Gill, Rye at Headwaters and Rye at Church Bridge, all having relatively small catchment sizes ranging from 4.6 km^2 at Blow Gill to 44.6 km^2 at Church Bridge. The only other site with relatively large d_{50} is Hodge Beck with a catchment area of 48.4 km^2. This site also has the highest SSY in the whole catchment.

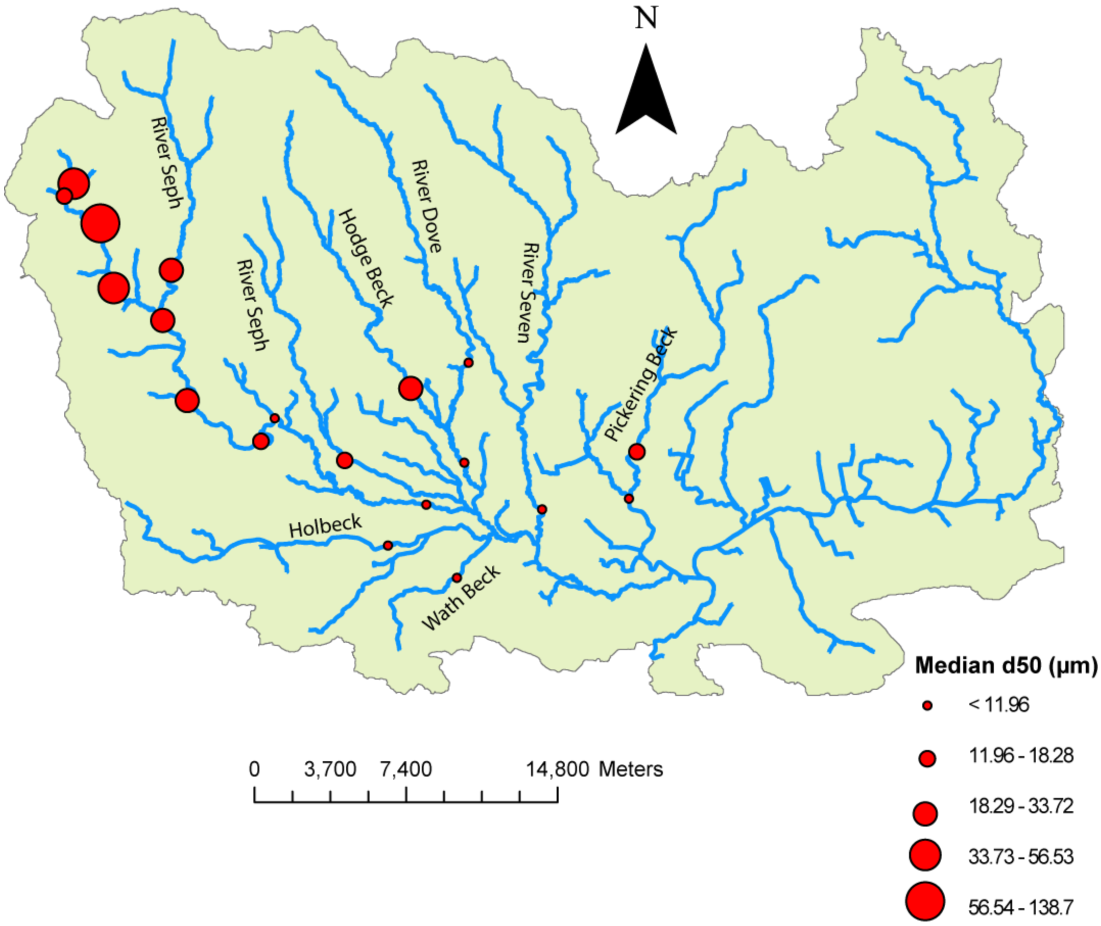


Figure 5.24: Map demonstarting the spatial variability in the median d_{50} particle sizes measured in the Upper Derwent catchment

The implications of these spatial restrictions is that with increasing distance downstream of the main Rye River, the median particle size decreases substantially from a d_{50} of 42.6µm at the headwaters to 12.0µm at West Ness (Table 5.1). Furthermore, the inter quartile range at the West Ness station is also very low at 8.3 - 14.8µm which falls within the fine – very fine silt range. Of interest is that between the headwaters (10.6 km^2) and Church Bridge (44.6 km^2) is that the particle size increases by 14.0µm, along with a considerably greater inter-quartile range. This increase in d_{50} is likely to be a consequence of the adjoining Arns Gill and Wheat Beck which have relatively large d_{50} values, whereas the increase at the lower end of the scale may be a result of fine sediment inputs dominating from Wheat Beck.

Site Name	Catchment Area (km^2)	d_{50} (μm)	IQ Range (μm)
Headwaters	10.6	42.6	22.1 – 78.6
Church Bridge	44.6	56.5	10.9 – 105.3
Broadway Foot	130.8	26.8	11.3 – 37.9
Mill Bridge	179.9	15.9	8.2 – 20.3
Helmsley	199.0	10.4	9.8 – 18.0
West Ness	236.3	12.0	8.3 – 14.8

Table 5.1: Particle size of fine sediment transferred in the main Rye River with increasing contributing area

This progressive winnowing of the coarsest material out of suspension and into storage as distance increases downstream of the steep headwater tributaries is also observed in the Esk catchment and is unsuprising given the longitudinal reduction in slope and current shear velocity (Davide et al., 2003), creating opportunities for within-channel storage and the selective deposition of coarser particles.

5.3.4 Temporal Variability in the Pattern of Suspended Sediment Particle Size

In the Esk catchment a clear annual pattern of median particle size variability was observed with maximum d_{50} values occurring in January 2008 and 2009 of the hydrological years. Unlike the Esk catchment, seasonal variability in d_{50} values is less marked (Figure 5.25). However, it is clear that in the three months prior to the maximum median d_{50} value which was obtained in the period ending the 18th March, median particle sizes consistently increase. Furthermore, in the successive three months to the period ending 27th June, the median particle size decreases to a minimum of 6.44 µm. This correlates well with the period of minimum particle size transfer in the Esk catchment also. However, clear trends are somewhat masked by the wide range in particle sizes being transferred across the catchment, with anything between clay and coarse sand sized material being transferred over the course of any single sampling period. For example, during the sampling period ending on 4th August 2009, the range in d_{50} values spanned from 5.76 – 135.7 µm with an inter-quartile range of 9.5 – 45.3 µm. This range in values is quite typical of the Upper Derwent catchment.

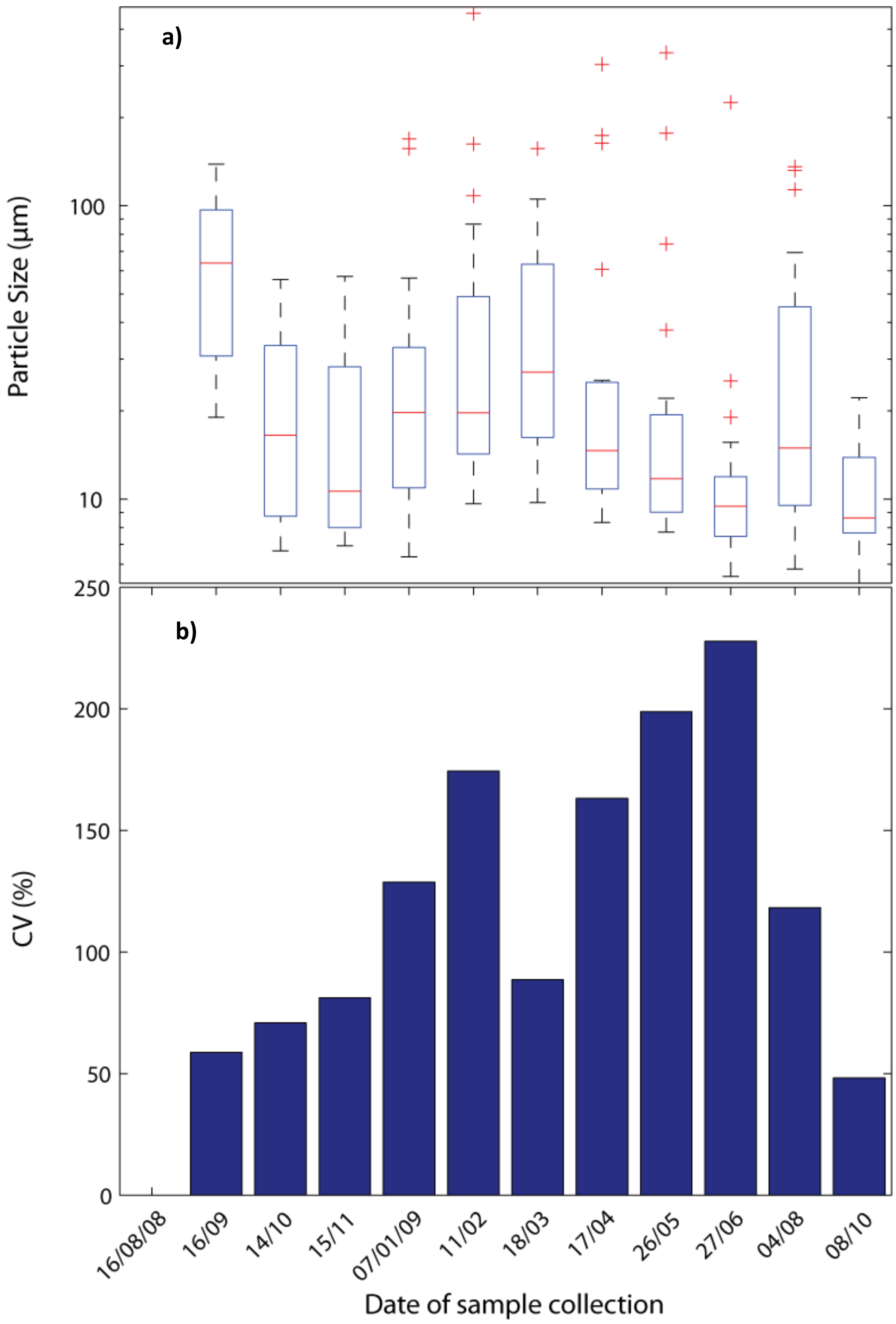


Figure 5.25: a) Monthly median particle sizes (µm) and; **b)** Coefficient of Variation (CV %) collected by TIMs across the Upper Derwent catchment. Note log scale on y-axis of particle size (µm).

5.3.5 Spatial Patterns in the Organic Content of Suspended Sediment

The minimum organic content obtained over this monitoring period was 2.8%, at the Arns Gill site. The greatest proportion of organic material of 25.1% was also obtained from the same site (Figure 5.26). This is a considerable range between the minimum and maximum values at one site and suggests the potential of episodic sources across this small catchment. Of the 183 measurements made, 147 (80.3%) lie within the 10 – 30% range typical of British rivers (Walling & Webb, 1987). 36 samples fall below the 10% lower boundary. These samples were obtained from all locations with the exception of Holbeck (at B1257 and East Ness) which have minimum values of 13.2 % and 15.5% respectively.

Throughout the monitoring period there is a great deal of within site variability at most locations across the catchment with the exception of Wath Beck, Holbeck at East Ness, Costa Beck and the River Seven. The organic content of sediment transferred through these predominantly lowland agricultural catchments is maintained at relatively stable and high levels (Figure 5.26). For example, Wath Beck was found to have the highest median value of organic content with the lowest inter-quartile range, perhaps highlighting that the range in sources within this catchment are minimal. This catchment is highly dominated by cereal production and grassland. The addition of fertilisers and organic wastes to the land in these areas are likely to produce high organic contents in the soil horizons (Haynes and Naidu, 1998) which may subsequently be mobilised. An alternative explanation is that the high organic content particles may be derived from clay material from the weathering products of the mudstones (Reynolds, 1986). The small d_{50} of transported sediment in this catchment provide support to the latter hypothesis.

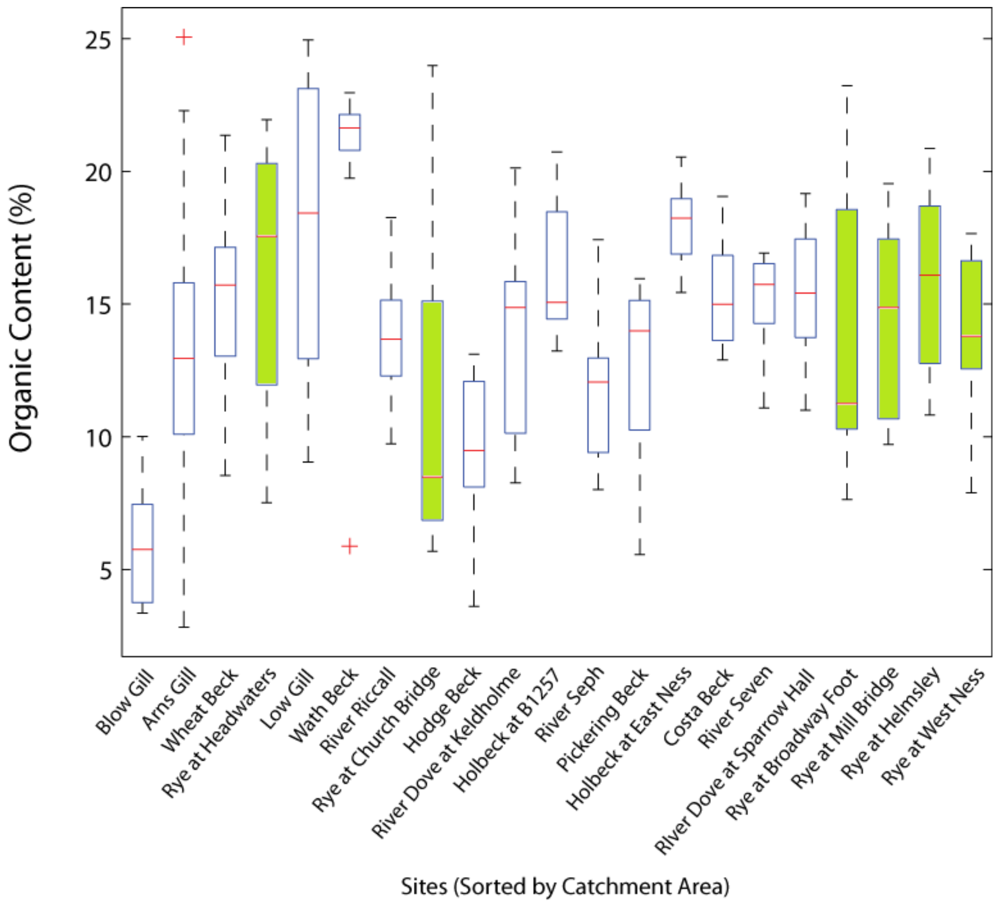


Figure 5.26: Box plots highlighting the spatial variability of organic content (%) between TIMs collection periods of approximately one month in the Upper Derwent catchment. Sites on the main Rye River are coloured green.

When compared with the data from other monitoring locations using the Wilcoxon-Mann-Whitney non-parametric test (Figure 5.27), this median value of 21.7% is significantly different ($P < 0.05$) than all other monitoring locations in the Upper Derwent with the exception of Arns Gill, Rye at Headwaters, Low Gill and Rye at Broadway Foot. Rye at Headwaters and Low Gill both have high median organic contents of 17.6% and 18.4% respectively, whereas Arns Gill and Rye at Broadway Foot are more moderate at 13.0% and 11.3% but have a large range in observed values.

Blow Gill is another site which is statistically different from all other sites due to the very low organic content measured here with a median value of 5.8 % and a maximum value which barely exceeds 10 %. This may be indicative of a catchment which is depleted in organic material. Hodge Beck also has significantly smaller median organic content than all other sites with the exception of Arns Gill, Church Bridge, River Seph, Pickering Beck and Rye at Broadway Foot. Additional differences are present between the site with the largest median value, Low Gill and all other stations with the exception of Arns Gill, Rye at Headwaters, Wath Beck and Broadway Foot.

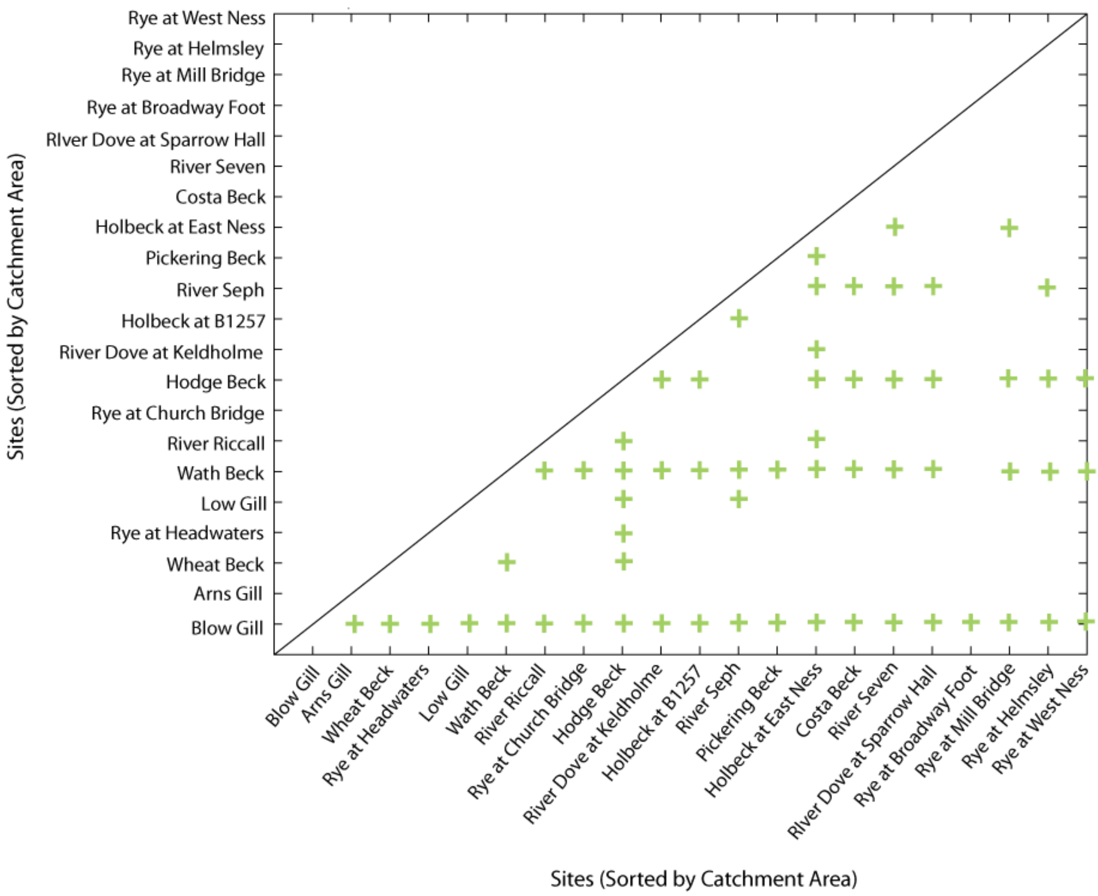


Figure 5.27: A summary of the statistically significant differences (P < 0.05) in organic content (%) at TIMs monitoring locations in the Upper Derwent catchment. The presence of a '+' illustrates significant differences between the two groups.

5.3.6 Temporal Variability in Patterns of Organic Content in Suspended Sediment

The considerable range in organic content (%) values between sites results in a high degree of variability on a monthly basis. For example, the smallest range in data post 16th September 2008 spans from 13.1 – 25.0% which was collected on 27th June 2009, whereas the largest range spans from 3.4 – 25.1% which was collected on 26th May 2009. This makes it difficult to distinguish any seasonal patterns in the data, with fluctuations on a monthly basis. The peak median organic content occurs on 27th June 2009 with a value of 18.3%. Organic content is at its minimum on the 18th March with a value of 10.8%.

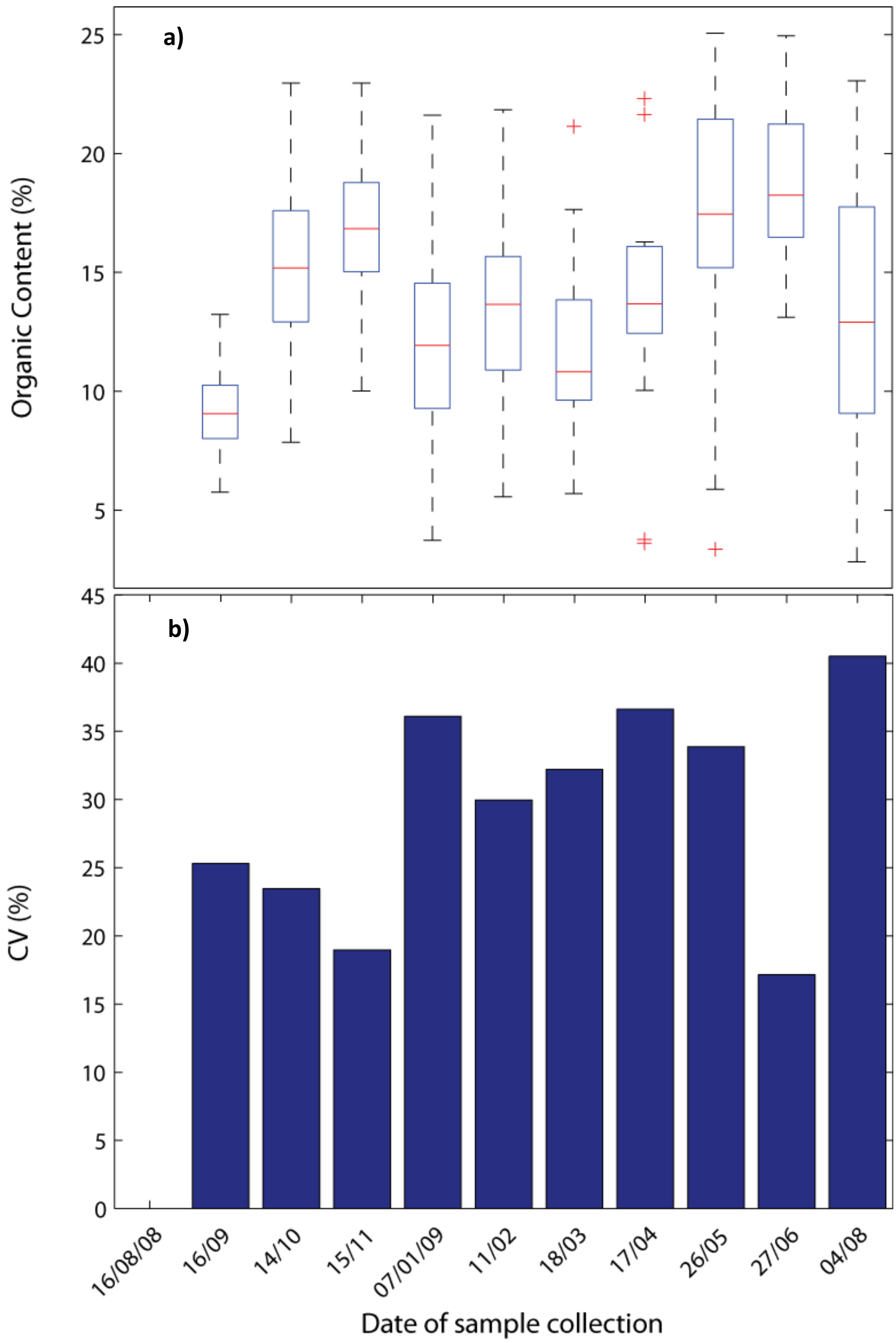


Figure 5.28: a) Monthly median particle sizes (µm) and; **b)** Coefficient of Variation (CV %) collected by TIMs across the Upper Derwent catchment. Note log scale on y-axis of particle size (µm).

5.3.7 Section Summary

This section has demonstrated how the quantity and physical properties of suspended sediment vary spatially and temporally at TIMs monitoring locations distributed throughout the Upper Derwent catchment. This analysis has found that:

(1) Along the main River Rye, suspended sediment loads (t) generally increase with contributing area. The magnitude of increase is fairly well scaled with catchment contributing area resulting in a fairly consistent SSY-A relationship. It may be that sources from within (and proximal) to the channel dominate or that inputs from tributaries in the lower reaches are important.

(2) Along the tributaries of the River Rye, peak SSYs occur in Hodge Beck whereas the minimum SSY is observed at Pickering Beck with sub-catchments draining the catchment to the south of the Rye producing relatively low SSYs. The headwater tributaries of the Upper Derwent catchment also have moderate to low specific yields.

(3) Sediment flux varies appreciably over the course of a year, with a considerable amount of variation occurring between sites during individual sampling periods.

(4) Areas of relatively coarse suspended sediment are limited to the headwater tributaries with evidence of significant downstream fining. There is little/no evidence of seasonal variability in the median particle size of sediment transported.

(5) A great deal of within-site variability in the organic content of SS is observed. The organic content of sediment transferred through the sub-catchments draining agricultural catchments is maintained at relatively stable and high levels. Organic content in headwaters is also moderate – high. The smallest proportions were collected from Blow Gill, Rye at Church Bridge and Hodge Beck. No discernible seasonal patterns in organic content were observed.

5.4 Comparison between Catchments

This chapter has begun to highlight some of the key broad scale patterns of fine suspended sediment flux and the properties of suspended sediment across the adjacent Esk and Upper Derwent catchments. A summary of the observations is provided in Figure 5.29. This diagram utilises the framework of analysis (Figure 5.1) with the findings of this chapter replacing the sub-section headings. This information allows us to begin to develop our understanding of the dynamics of fine sediment transfer, which will be developed further through the analysis conducted at high temporal resolutions at specific locations in the catchments (cf. Chapter 6).

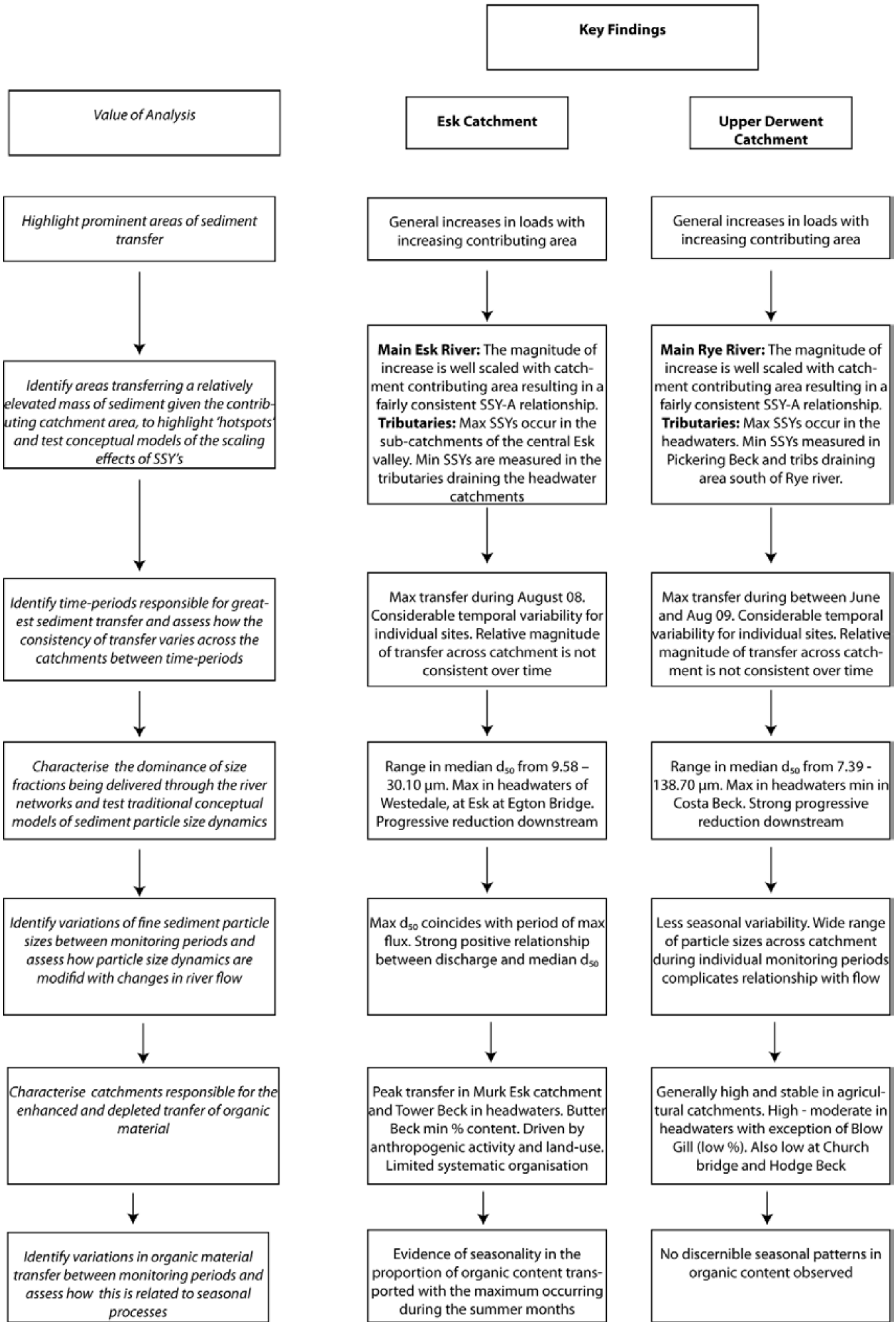


Figure 5.29: A comparison of the key findings from the Esk and Upper Derwent monitoring campaign

Chapter 6: Temporal Variability in Suspended Sediment Transfer

6.1 Chapter Overview

This chapter seeks to enhance our understanding of the way in which fine sediment is transferred through river networks in the upland catchments of the Esk and Upper Derwent. The relatively limited research conducted in these environments (compared to lowland environments) means that furthering of our understanding of upland sediment transfer processes has the potential to be of vital importance in tacking the physical, ecological, economical and legal issues associated with elevated sediment flux (cf. Chapter 2).

The analysis of high-quality, quasi-continuous sediment flux measurements at two locations along the main Esk River and one along the River Rye in the Upper Derwent catchment will provide the basis for understanding catchment-wide sediment yield dynamics and provide an insight into the sediment delivery processes operating at different scales. When coupled with the analysis of within-storm fine suspended sediment dynamics (which provides a direct measure of source ascription) and the understanding of transfer hotspots from the TIMs sampling network (cf. Chapter 5), the spatial variability of sources and transfer of sediment can be understood in a way which is physically meaningful and consistent with assessments at the meso-scale which are not frequently conducted. An overview of the analysis framework and an assessment of how each element of the analysis contributes to the development of the conceptual model are outlined in Figure 6.1.

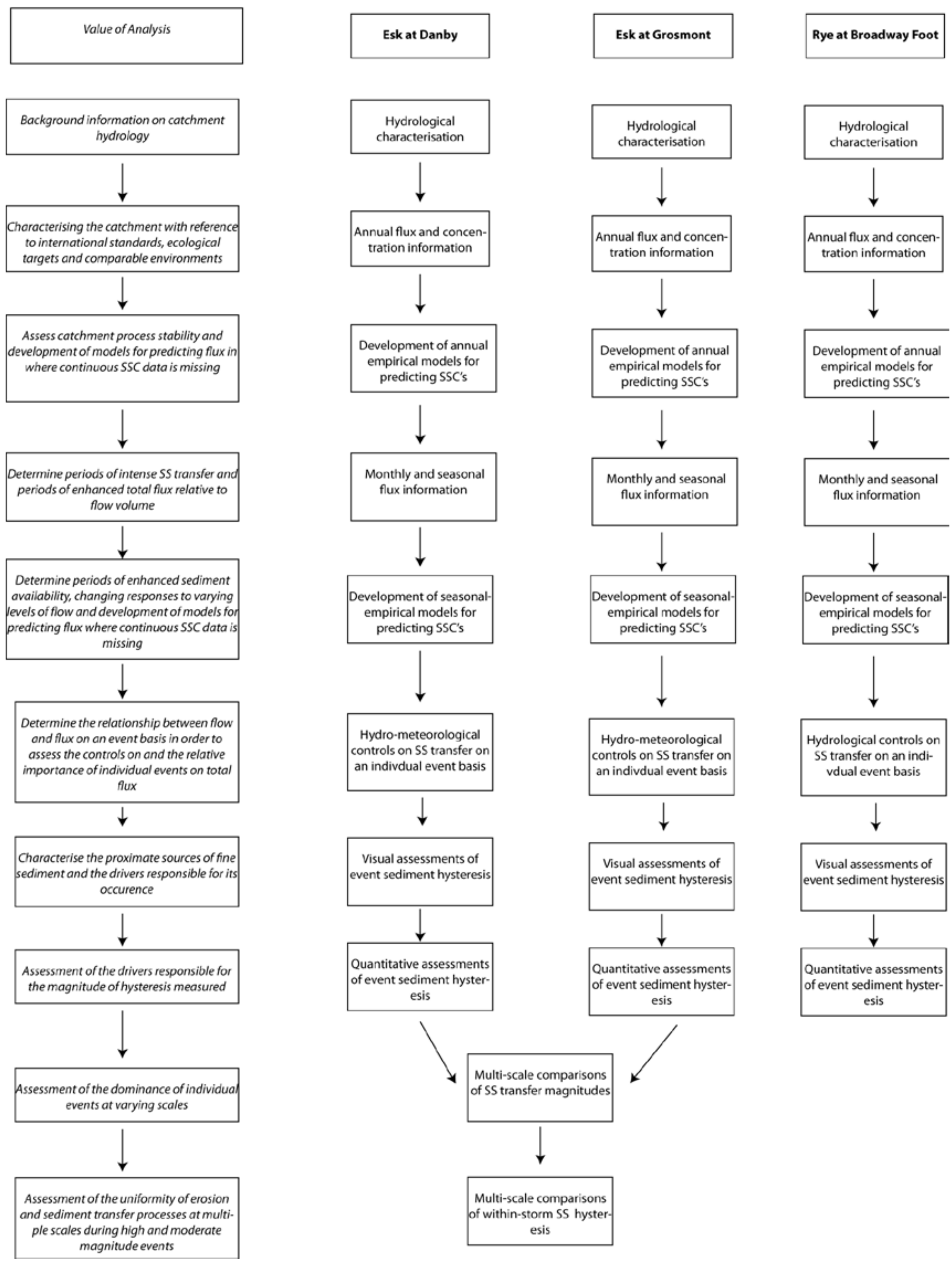


Figure 6.1: Framework showing the elements and linkages between analysed components and their contribution to understanding of sediment transfer in the Esk and Upper Derwent catchments

6.2 River Esk at Danby

Monitoring of water level and SSCs at Danby on the River Esk began on 1st October 2007 and continued until 14th September 2009, providing nearly two complete hydrological years' monitoring data.

6.2.1 Hydrology

Over the two year monitoring period, the total water yield was 98.46 hm^3 with discharge ranging from 0.31 to 63.07 $m^3\ s^{-1}$, with the maximum discharge occurring during a storm on the 13th December 2008. The mean value over this period is 1.62 $m^3\ s^{-1}$ with a coefficient of variation of 247.44%. In the 2007/08 and 2008/09 hydrological years the annual water yield varies from 54.18 to 44.28 hm^3 with a range in discharge of 0.33 – 62.53 $m^3\ s^{-1}$ and 0.31 – 63.07 $m^3\ s^{-1}$ respectively. The mean discharge for each year is 1.71 and 1.55 $m^3\ s^{-1}$ with associated coefficient of variations of 231.65 and 266.65%.

	2007/08	**2008/09**
Water yield (hm^3)	54.18	44.28
Flow range ($m^3\ s^{-1}$)	0.33 – 62.53	0.31 – 63.07
Mean discharge ($m^3\ s^{-1}$)	1.71	1.55
CV of mean discharge (%)	231.65	266.65

Table 6.1: Hydrological characteristics of the Esk catchment monitored at Danby

6.2.2 Annual Suspended Sediment Transfer

At the start of the first sampling year, technical difficulties in measuring turbidity meant that flux was not monitored until 22nd November 2011. However, this missing record was later filled extrapolated data for the 2007/08 annual sediment rating curve (Table 6.1). The average SSC for the entire monitoring period is 26.31 mg L^{-1} with a coefficient of variation (CV) of 188.40%, highlighting the large amount of variability during the year. The maximum SSC was measured during a storm event on 29th March 2008, where it peaked at 827.95 mg L^{-1}. The between year variability in SS transport is quite limited. In the 2007/08 and 2008/09 hydrological years, the SSCs vary from 0.01 – 827.95 mg L^{-1} and 0.12 – 786.74 mg L^{-1} respectively which are well within the operating limits of the probe. The mean SSCs for each year are 26.67 and 24.13 mg L^{-1} with associated CVs of 180.49 and 197.83%.

For each monitored year, the relationship between SSC and discharge is positive and statistically significant ($P < 0.001$), with explained variance of 43.0% and 46.8% for years one and two respectively. Following bias correction, relative errors are in the region of -5.79 and -9.74%. The rating coefficients between the years (Table 6.2) are remarkably similar, suggesting that the processes governing SS transfer are reasonably stationary. However, the degree of scatter between SSCs and discharge is considerable, highlighting that, although river flow is a dominant driver of SS flux, variability in the relation may occur as a product of SS availability in the catchment. The relation between the two variables is demonstrated in Figure 6.2.

a) b)

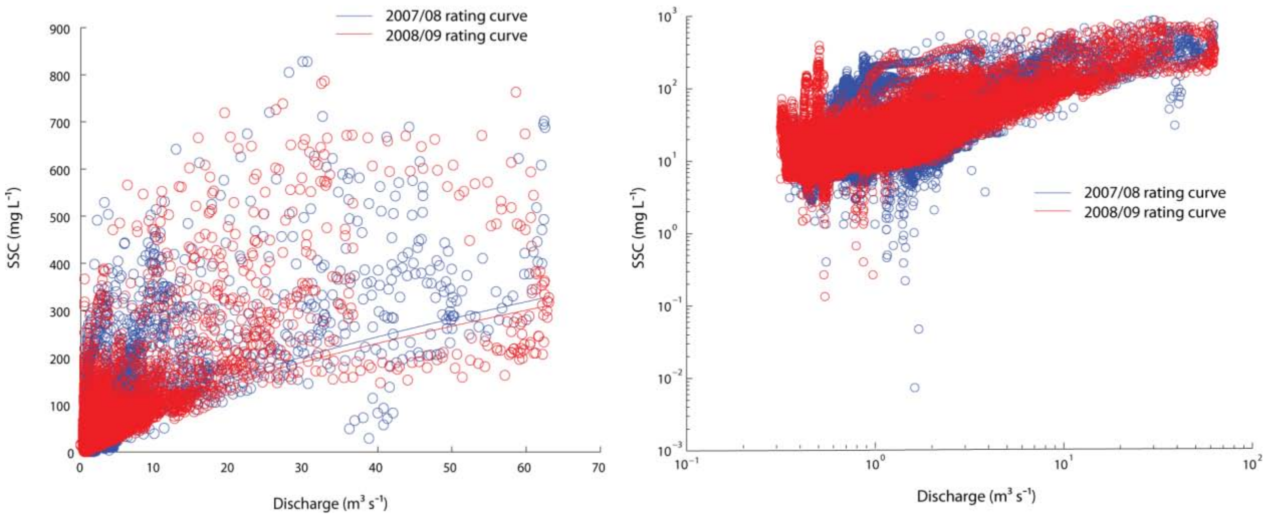


Figure 6.2: Annual sediment rating curves for Danby, river Esk in **a)** normal space and; **b)** log space.

Water Year	*n*	Sediment Load (t)	90% transported in...	*a*	*b*	Log-normally distributed error	Coefficient of Determination (R^2)	*P*	Relative error of Estimation (%)	Duan (1983) correction factor	Relative error of estimation (%) After SF
2007/08	35136	5544.5 (± 1136.1)	9.86%	15.8732	0.6835	0.0832	0.4301	*< 0.001*	-27.2576	1.2951	-5.7914
2008/09	33471	5425.1 (± 1111.6)	4.62%	16.7179	0.6567	0.0618	0.4675	*< 0.001*	-24.5885	1.2207	-7.9445

Table 6.2: Summary of annual sediment loadings and annual sediment rating curve parameters at Danby, river Esk

Following the integration of simultaneous river flow and SS measurements, the annual SS load was calculated. In the first sampling year, it is estimated that 5545.5 (± 1136.1) t of fine sediment was transported through the river reach equating to a sediment yield of 57.91 (± 11.87) t km^{-2}. During the second sampling year, 5425.1 (± 1111.6) t of fine suspended sediment was transferred, equating to 56.66 (± 11.61) t km^{-2}. The suspended sediment loadings over the two monitored years are remarkably similar with minimal transfer occurring under low flow conditions. This is highlighted by 90% of the total suspended sediment load being transported in 6.70% of time. For the first year of sampling, this figure is 9.86%, which falls to 4.62% during the second year (see Table 6.2):

6.2.3 Monthly and Seasonal Variability in Suspended Sediment Transfer

Within and between seasons, strong monthly fluctuations in the fine suspended sediment transfer occur, which are largely a function of the total monthly water yield. However, there is little observable structure in the timing of fine sediment flux which is demonstrated in Figure 6.3. The mean monthly suspended sediment load is 488.99 tonnes (CV = 100.45%). Between the two sampling years, there is little change in this value, with a slight decline from 533.26 t (CV = 91.90%) to 514.73 t (CV = 104.64%).

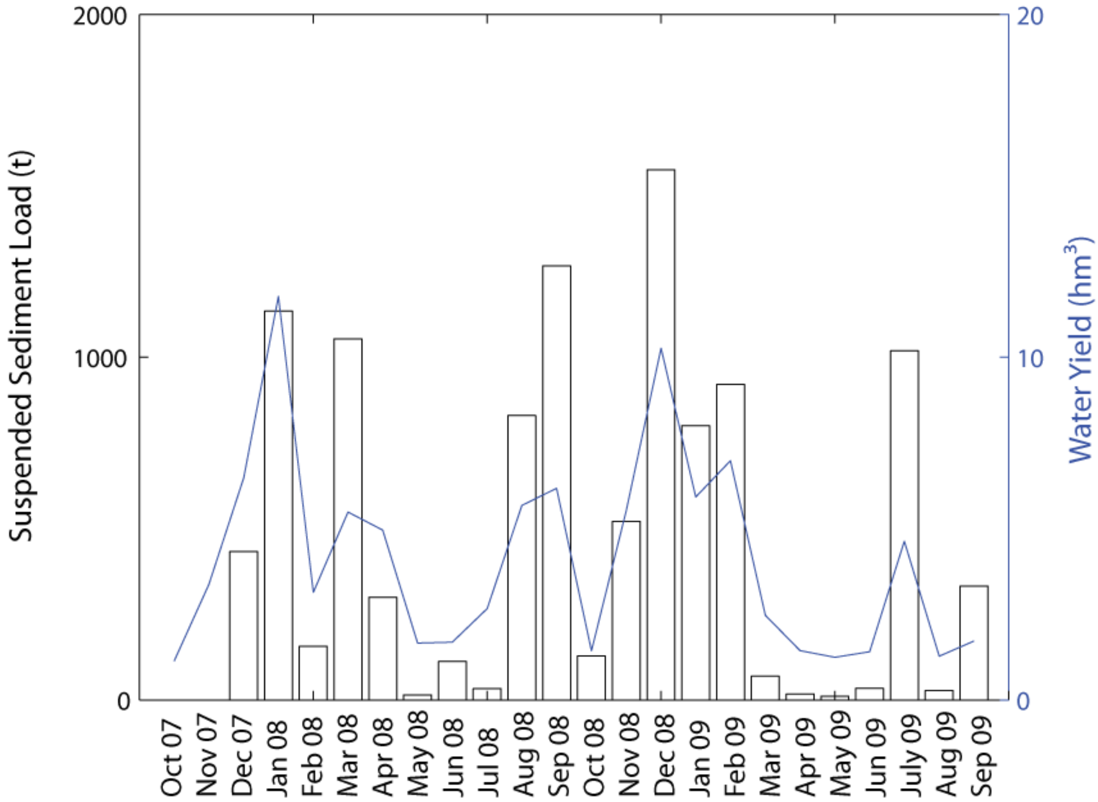


Figure 6.3: Monthly suspended sediment load (t) and water yield (hm^3) at Danby, river Esk

The seasonal SS loads are also quite varied throughout the monitoring period with individual season's contributions to the annual load varying between years. Although, the spring months do contribute the least to the annual load for both years one and two with 1300.1 and 63.6 t respectively. The periods of highest SS transfer occur in autumn, summer 08 and winter 08/09, which cumulatively transfer 6112.5 t of fine suspended sediment. The seasons with the largest total sediment loads (summer and autumn 08) also contain the two greatest individual monthly suspended sediment loadings. These are December 08 (1546.8 t) and September 08 (1266.4 t).

The relationship between monthly water yields and SS load reveals periods of the year where there is a relative depletion and also abundance of fine sediment available for transfer. These periods can be picked out visually and through the analysis of the multiple hysteresis loops of varying strengths, complexity and directions (Figure 6.4). Year 1, which represents the 2007/08 hydrological year, shows one distinct hysteresis loop. The total water yield for December 07 is moderately high (6.48 hm^3), with a moderate total monthly sediment load (432.65 tonnes). From this starting point, water yield increases during January 08 to the maximum value over the entire monitoring period (11.78 hm^3). However, the associated sediment load is only the second highest (1134.9 tonnes), which highlights potential relative depletion compared to March, which has a water yield of 5.48 hm^3 and sediment load of 1053.5 tonnes. March also represents the peak in the clockwise hysteresis observed in year one. In the following month of April, the total water yield is maintained (4.96 hm^3). However, the suspended sediment load is markedly reduced (299.67 tonnes). Water yield and sediment load then continue to fall during May 08, which closes the clockwise hysteresis loop. The following two months are also relatively dry with little sediment transfer in the upper reaches of the catchment. However, this is broken by the occurrence of two months of moderate water yields (5.67 and 6.17 hm^3 respectively), which produce a relatively large mass of fine suspended sediment (829.43 and 1266.4 t respectively).These patterns of monthly sediment transfer in relation to total load reveal that availability of fine sediment is fairly even throughout the year, except in the months of March, August and September, where a relative abundance of sediment sources appear to prevail.

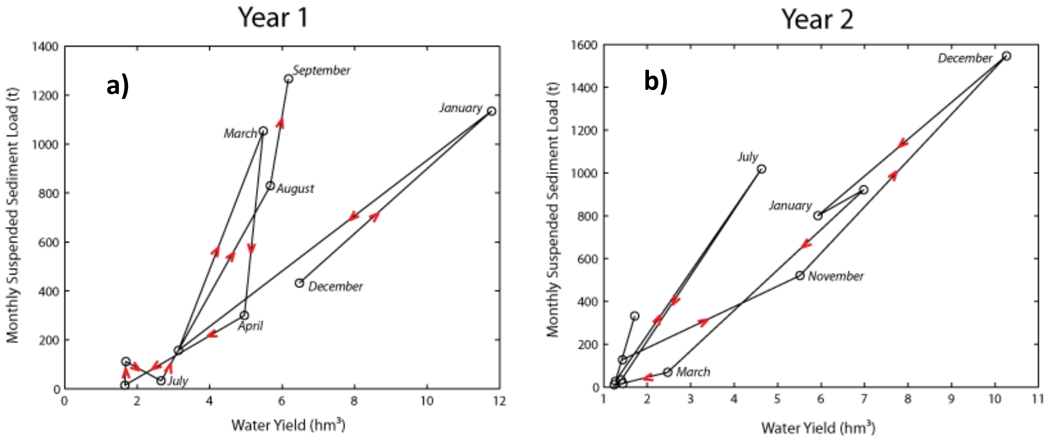


Figure 6.4: Monthly water yield and sediment load hysteresis patterns at Danby, river Esk for the **a)** 2007/08 and; **b)** 2008/09 hydrological years

In the second year of monitoring, the first evidence of seasonal hysteresis occurs at the beginning of the 2008/09 hydrological year. During October, both the water yield and sediment load are low (1.43 hm^3 and 128.18 tonnes respectively). The water yield and sediment load then increase during the subsequent months of November and December 08, when the peak in both total water yield and sediment load are reached (10.26 hm^3 and 1546.8 tonnes respectively). In January, the water yield decreases substantially, to a value comparable to that of November 08 (5.92 hm^3). However, the sediment load is 54% greater. In February the total water yield then increases slightly along with the sediment load, before falling dramatically in March 09 to 2.47 hm^3. This produces anti-clockwise hysteresis which suggests that there may be a relative enhancement of sediment sources in January and February 09 compared to those in November 08.

Following this period of peak water yield, March to June represents a period of time where flow and sediment transfer is somewhat diminished. However July 09 represents a month whereby the water yield increases from 1.40 hm^3 to 4.63 hm^3, a 329 % increase which is met by a 3030% increase in monthly sediment load. However, this period of mobilisation is short lived with water yield and total sediment load falling to 1.27 hm^3 and 27.67 t during

August 09. In both years, an extended period of low total water yield and sediment load is broken by a pulse in sediment transfer when water yield increases once again. In year one this enhanced mobilisation occurs relatively early in the year (March), whereas during the second year, this is delayed until July due to a lack of meteorological forcing. In the first year of monitoring, there is a further pronounced peak in suspended sediment loads, during August and September 08 which is not observed during the second year.

Although these hysteresis patterns are complex, some similarities have been found between the years which may indicate there are some larger scale catchment processes acting to enhance/restrict the sediment availability over course of a year. The autumn months account for a considerable proportion of the annual water yield there may be a relative depletion in fine sediment available for mobilisation for a given flow magnitude, with the periods of relatively low flows occurring in July (2008) and August and September (2009) producing comparable monthly loads without the same magnitude of total water yield.

In order to further better understand variations in sediment transfer in the catchment, additional analysis involving development of seasonal rating curves was conducted. The parameters of these models, along with statistical summary information are provided in Table 6.3.

	n	Sediment Load (t)	*a*	*b*	Log-normally distributed error	Coefficient of Determination (R^2)	Relative error of Estimation (%)	B*	Relative error of estimation (%) After SF
Autumn 07[a]	2765	---	12.23	0.7352	0.0824	***0.42***	-23.4863	*1.1954*	-8.5388
Winter 07/08	8736	1479.2	14.56	0.5756	0.1011	***0.30***	-33.3595	*1.4191*	-5.4324
Spring 08	8832	1300.1	14.78	1.0422	0.0615	***0.67***	-15.3280	*1.2472*	5.6032
Summer 08	8832	2124.6	20.11	0.6246	0.0578	***0.49***	-22.6688	*1.2019*	-7.0786
Autumn 08	8736	2194.7	17.47	0.6325	0.0578	***0.50***	-22.2202	*1.2252*	-7.7073
Winter 08/09	8640	1793.2	11.27	1.0248	0.0280	***0.77***	-11.0381	*1.0894*	-3.0838
Spring 09	8833	63.6	18.13	1.1613	0.0201	***0.49***	-10.1392	**1.1163**	0.3108
Summer 09	8222	1382.4	28.96	0.6619	0.0399	***0.50***	-14.4572	*1.1278*	-3.5249

Table 6.3: Summary of seasonal suspended sediment transfer at Danby, River Esk. * Duan (1983) in italics, Kao (2005) in Bold, [a] Data collected during autumn 2007 is not complete therefore no load has been given. All data is statistically significant ay the 99.9% level

The *a* and *b* coefficients of the developed seasonal rating curves represent the rating parameters and essentially have no physical meaning. However, these coefficients have often been used to provide information about the nature of sediment transfer in the monitored catchments. The a-coefficient is typically interpreted as providing information about the severity of erosion in the catchment, with high values indicating intensively weathered materials which are readily available for transport under low flow conditions (Morgan, 1995). The b-coefficient is typically interpreted as representing the erosive power of the river, with large values being indicative of systems where increases in flow result in marked increases in sediment flux (Asselman, 2000), although, the value of the b-coefficient can be confounded by the dominance of coarse silt or sand in the available sediment stock due to transport of coarser particles being initiated only once a stream power threshold is exceeded (Walling, 1974).

Analysis of the seasonal rating coefficients developed for the Danby monitoring station indicate that the sediment availability is at its minimum (minimum a-coefficient) occurs during winter 2008/09 whereas the greatest sediment availability under low-flow conditions (maximum a-coefficient) occurs in the summer months of 2008 and 2009 (20.11 and 28.96 respectively). These summer months also account for two out of the three smallest *b*-coefficient values (0.6246 and 0.6619), highlighting a relatively dampened response to increases in flow. These summer months represent a period of considerable sediment transfer with 2124.6 t of fine sediment being transferred during 2008 and a more moderate 1382.4 t during 2009. During both years, this period is one of relative abundance of fine sediment availability for the total water yield (according to monthly hysteresis analysis). This potentially indicates the importance of sediment transfer during low magnitude events.

Sediment concentrations respond most sensitively to increases in flow (maximum b-coefficient) during spring 2008 and 2009 (1.0422 and 1.1633 respectively). During the 2008 season, moderate SS flux in the order of 1300.1 t occurs with the vast majority of transfer occurring at the end of March, with negligible transfer during May. From the monthly hysteresis plots it has been shown that March represents a large flux despite a moderate total water yield. The occurrence of high sediment availability whilst producing a rating curve with a maximum b-coefficient may indicate that the sediment available for transfer during this period was at the elevated ranges of river flow for the period in question. During the second year, the negligible flux (63.6 t) makes interpretation of the coefficients difficult.

Analysis of the relationship between the rating coefficients can also be of use in characterising the sediment transport system. Research has commonly found strong negative relationships between the *a* and *b*-coefficients of sediment rating curves developed for individual catchments (e.g. Asselman, 2000; Fenn et al., 1985; Rannie, 1987; Thomas, 1988; Walling, 1977). This can occur due to one of two situations; either the presence of easily accessible and erodible sediment stock results in increases in discharge having little influence in the SSCs, producing flat rating curve (high a and low b-coefficients); or, catchments that consist of resistant material are highly affected by stream power which inevitably produces steep rating curves (low a and high b-coefficients). Morehead *et al*. (2003) suggested that the strength of this relationship is indicative of the inter-annual variability in the SSCs for a given discharge, with less variability indicating less temporal variability.

When the seasonal *a* and *b*-coefficients developed at the Danby monitoring station are regressed against each other, no statistically significant relationship between the variables is found. This highlights the complex control over sediment production, depletion and transfer existing in the upper Esk valley with inconsistencies in the sediment yield processes at varying times of the year. These complexities will now be examined in further detail through analysis of the within storm fine sediment dynamics.

6.2.4 Within-Storm Sediment Dynamics

6.2.4.1 Importance of Infrequent Events

The analysis of seasonal and monthly fine sediment flux dynamics has highlighted time periods of the year which are responsible for the transfer of fine suspended sediment in the Esk catchment above the Danby monitoring station. However, on a shorter time-scale there is often a large amount of variability in the timing of fine sediment transfer, with a substantial mass of sediment often being transported in a very short period of time. This is exemplified by 1392 t of sediment being transferred in just two days during December 2008 and 916.7 t in just over one day during July 2009. This mass equates to 25.11% and 16.90% of the total annual loads respectively. Given the importance of these very short periods for the transfer of a considerable proportion of the annual flux, it may be appropriate that the time-unit for analysis is much shorter than has already been undertaken, with focus being on the within-storm fine suspended sediment dynamics of episodic transfer events.

During this monitoring period in the River Esk catchment above Danby, 82 visually defined sediment transfer events were recorded. Analysis of the hydro-meteorological conditions and the timing of the peak suspended sediment pulses is undertaken. This allows some inferences to be made about the processes responsible for the delivery and transfer of fine fluvial sediment.

6.2.4.2 Hydro-meteorological Controls on Event Flux

Initially, the extent to which the event suspended sediment load (tonnes) could be predicted by; (a) peak event discharge ($m^3 s^{-1}$); (b) event max rainfall intensity ($mm hr^{-1}$); (c) event rainfall total (mm) and; (d) antecedent rainfall total (mm over previous 5 days) was examined. This was done through the production of a scatter plot matrix. This highlighted that the peak discharge was the main descriptor for the variation in suspended sediment loads ($R^2 = 0.89$; $p < 0.001$), with only total rainfall amount (mm) out of the meteorological variables providing a statistically significant relationship ($R^2 = 0.25$, $P < 0.001$). However, the RMSE of 195.32 highlighted the considerable degree of error in the predictions. Rainfall intensity and antecedent conditions were statistically insignificant at the 95% level.

This analysis has shown that hydrological variables, and to a lesser extent, meteorological variables are able to predict the event suspended sediment load in the Esk catchment above Danby. Significant correlations between total precipitation, peak discharge, total water yield, flood intensity and sediment variables during flood events have also been documented in other agricultural environments (Oeurng et al., 2010).

6.2.4.3 Assessment of Event Hysteresis Patterns

Visual examination of the pattern of hysteresis was conducted on the 82 flow events, the summary of which is provided in Table 6.4. The data demonstrates that clockwise events are the most frequent, accounting for 43.9 % of the total number. They are also responsible for the vast majority of fine sediment, with a median value 15 times greater than that of anti-clockwise events. After performing a Wilcoxon-Mann-Whitney non-parametric test, it was confirmed that statistically significant differences exist between the clockwise and anti-clockwise groups' event median ($P < 0.001$). The median value of sediment loads during clockwise events is also over 5 times that of events with nearly no hysteresis ($P < 0.001$). No other significant differences were found.

Further analysis focussed on the extent to which the type of hysteresis exhibited during the storm events was controlled by meteorological conditions. Differences between the meteorological characteristics for each hysteresis condition were tested. It was found that significant differences exist in the event maximum rainfall intensity and the total rainfall amount for clockwise and anti-clockwise events ($P = 0.004$ and $P = 0.0013$ respectively) and also the total amount of rainfall during clockwise events and events with nearly no hysteresis ($P < 0.001$). However, no statistically significant differences between the hysteresis conditions were found for the antecedent rainfall amount.

Hysteresis Condition	Number	Median event total Load (t)	Median absolute deviation of load (t)	Median event max rainfall intensity(mm hr^{-1})	Median event rainfall total (mm)	Median Antecedent rainfall total (mm over previous 5 days)
Clockwise	36	97.47	91.58	2.80	12.60	12.80
Anti-clockwise	18	6.47	2.80	1.60	6.60	19.80
Figure of Eight (anti-clockwise loop)	4	21.32	9.08	1.70	3.70	3.00
Figure of Eight (clockwise loop)	1	4.15	---	4.8	6.20	35.80
Nearly none	23	18.61	15.56	2.20	6.20	13.20

Table 6.4: Summary of hysteresis patterns and meteorological conditions observed at Danby, river Esk

These findings indicate that the meteorological conditions during the course of an event do have an influence on the non-linear relationship between flow and SS. Rainfall events of high intensity, producing high rainfall totals, are likely to produce events demonstrating clockwise hysteresis with large suspended sediment loads. This is a similar mechanism to that observed in other environments, whereby convective storms lead to infiltration-excess overland flows and the production of Q-SSC relations that display clockwise hysteresis properties (Alexandrov et al., 2007). However, given that clockwise events are characteristic of sediment sources close to the channel, a more logical explanation is perhaps that large flow events which occur rapidly generate high shear stresses within the channel, resulting in the mobilisation of in-stream sediment sources. A secondary explanation may be the activation of channel bank sources through collapse and failure, although previous research has suggested that most bank failures may occur following the peak in the hydrograph (Luppi et al., 2009; Rinaldi et al., 2004). The high correlation between event sediment loads and peak discharge (R^2 = 0.89) also supports this argument for within channel sediment sources.

As has been identified, there is limited SS transfer in the Esk catchment during events which are best characterised by anti-clockwise hysteresis. In this catchment these events are characterised by rainfall events of low intensity (median of 1.60 mm hr^{-1}) and moderate total rainfall amounts (median of 6.60 mm). This lag in SS response may indicate sediment sources from distal areas of the catchment although this explanation may be complicated in this instance.

At the Esk above Danby, anti-clockwise events only occur under relatively low intensity rainfall conditions, which would not typically be associated with sediment flux from distal sources. For example, it has previously been shown that the process of gentle wetting across a catchment may result in the increasing cohesion of the surface sediments (Alexandrov et al., 2007) resulting in the restriction of fine sediment movement on the hillslope.

An additional factor to consider is the timing of these events, with 50% occurring during the summer months. Analysis of the seasonal rating curve coefficients has demonstrated that SSCs are relatively high under low-flow conditions with sediment availability being highest during these periods. Such seasonal variability in the sediment delivery process has previously been identified to be as a result of changing soil conditions. For example, Gregory & Walling (1973) explained higher concentrations during summer by assuming reduced base-flow contributions, with a dry soil surface contributing to a flushing effect. Sayer (2006) furthered this by suggesting that the act of drying and soil faunal activity between storms may condition the soil surface to become readily entrained in subsequent wet periods. Alternatively, seasonal agricultural practices may be an important factor. It has previously been shown that tillage for cultivation may promote high SSCs in June and July due to a loosening of the soil surface, thereby increasing soil erodibility (Li et al., 2010). Alternatively, these conditions may simply be a product of bank-side collapse during the falling limb of the hydrograph.

The explanations posed for the explanation of anti-clockwise events are somewhat different to those described by Seeger *et al.* (2004) in which anti-clockwise events were generated as a consequence of significantly higher precipitation levels with high soil moisture content, leading to the generation of high SSCs during the event. In the situation described by Seeger *et al.* (2004), SS sources are extensively distributed throughout the catchment, with areas that infrequently connect to the drainage network becoming activated during these spatially extensive events.

Unlike Seeger's (2004) findings, the antecedent soil moisture conditions appear to have no bearing on the direction of hysteresis which further highlights the limited potential contribution from hillslope sources. The 'nearly no hysteresis' group had the greatest relative error for each of the meteorological descriptors; highlighting a complex interaction of processes that are responsible for the occurrence of this condition.

6.2.4.4 Quantitative Assessment of Event Hysteresis Patterns

This research has demonstrated the significance of rainfall intensity and rainfall total in differentiating between the directions of hysteresis over the course of two hydrological years monitoring in the Esk catchment above Danby. Therefore analysis was expanded to examine the ability of meteorological conditions to predict the magnitude of hysteresis. This magnitude of hysteresis was determined through calculation of the hysteresis index which as introduced earlier is a measure of the difference in SSCs on the rising and falling limb's of the hydrograph at the median event flow with positive values representing larger SSCs on the rising limb and negative values representing larger SSCs on the falling limb. The magnitude of the index represents the degree of hysteresis (Lawler et al., 2006). The mean and median of the index are both positive, at 0.20 and 0.11 respectively, with minimum and maximum values of -2.42 and 2.67 respectively. The standard deviation of the data is 0.89.

Following partitioning of the data into negative and positive groupings, a Wilcoxon-Mann-Whitney non-parametric test was conducted. Statistically significant differences between negative and positive groupings for median suspended sediment loads were obtained ($Z = 4.14$; $P < 0.001$). Subsequently, a correlation matrix between measured meteorological and hydrological variables and hysteresis index was produced. The rainfall intensity and AMC did not produce statistically significant estimations of the hysteresis index. However, the event maximum discharge ($m^3 s^{-1}$) and the event rainfall total (mm) did sufficiently account for the variability in the hysteresis index. The derived regressions are shown in Equations 6.1 and 6.2 where x are event maximum discharge ($m^3 s^{-1}$) and the event rainfall total (mm) respectively.

$y = -0.1103 + 0.0282x$ ($R^2 = 0.28$; $P < 0.001$) Equation 6.1

$y = -0.3346 + 0.0505x$ ($R^2 = 0.24$; $P < 0.001$) Equation 6.2

6.2.5 Section Summary

This section has demonstrated how the transfer of suspended sediment varies temporally in the Esk River above the Danby monitoring station. This analysis has found that:

(1) The between year variability in SS transport is limited. In the 2007/08 and 2008/09 hydrological years, the SSCs vary from 0.01 – 827.95 mg L^{-1} and 0.12 – 786.74 mg L^{-1} respectively. The mean SSCs for each year are 26.67 and 24.13 mg L^{-1}.

(2) For the 2007/08 and 2008/09 hydrological years, the annual sediment loads were 5545.5 (± 1136.1) t and 5425.1 (± 1111.6) t respectively equating to 57.91 (± 11.87) t km^{-2} and 56.66 (± 11.61) t km^{-2} respectively

(3) Simple rating curves are able to predict SSCs from discharge measurements, providing a useful means of estimating flux at this location in the short-term where only Q data exist.

(4) Within and between seasons, strong monthly fluctuations in the fine suspended sediment transfer occur, which are largely a function of the total monthly water yield although some hysteresis is observed. Periods of highest SS transfer occur in autumn, summer 08 and winter 08/09.

(5) The efficiency of rating curve predictions can be improved by developing seasonal models. Analysis of the seasonal rating curve parameters highlights relative sediment source depletion under low-flow conditions during winter 2008/09 with greatest sediment availability in the summer months of 2008 and 2009. SSCs respond most sensitively to increases in flow during spring 2008 and 2009.

(6) Regression analysis between the *a* and *b*-coefficients has highlighted the inconsistencies in the sediment yield processes at varying times of the year.

(7) Peak event discharge is a very good predictor of event sediment load ($R^2 = 0.89$; $P < 0.001$). Total rainfall amount (mm) also provides a statistically significant relationship ($R^2 = 0.25$, $P < 0.001$).

(8) Clockwise hysteresis events are the most frequent (43.9 %) and transport the vast majority of fine sediment, with a median load value 15 times greater than that of anti-clockwise events. The median load transported in these groups is statistically different.

(9) Meteorological conditions influence the non-linear relationship between flow and SS. The maximum rainfall intensity and total rainfall amount for clockwise and anti-clockwise events was significantly different with clockwise values being greater.

(10) 50% of anti-clockwise events occur during summer months which may be related to the soil and land-cover conditions at this time.

(11) Statistically significant differences between negative and positive groupings for median suspended sediment loads were obtained with higher values for the positive events. Event maximum discharge (m^3 s^{-1}) and the event rainfall total (mm) can be used to predict the magnitude of hysteresis observed.

6.3 River Esk at Grosmont

Monitoring of water level and SSCs at Grosmont on the River Esk began on 29th January 2008 and continued until 27th July 2009, providing 18 months of continuous data.

6.3.1 Hydrology

Over the 18-month monitoring period the total water yield was 187.56 hm^3 with discharge ranging from 0.65 to 233.18 $m^3\ s^{-1}$, with the maximum discharge occurring during a storm on the 6th September 2008. The mean value over this period is 3.96 $m^3\ s^{-1}$ with a coefficient of variation of 192.58 %. In the first 8 months of monitoring through to the end of the first water year (30th September 2008), the total water yield is 80.15 hm^3 with a range in discharge of 0.85 – 233.18 $m^3\ s^{-1}$. The mean discharge is 3.81 $m^3\ s^{-1}$ with a coefficient of variation of 198.51 %. In the following 9 months from 1st October through to the end of the monitoring period, the total water yield is 107.41 hm^3 with a range in discharge of 0.65 - 158.98 $m^3\ s^{-1}$. The mean discharge is 4.11 $m^3\ s^{-1}$ with a coefficient of variation of 189.56 %.

	January 08 – September 08	**October 08 – July 09**
Water yield (hm^3)	80.15	107.41
Flow range ($m^3\ s^{-1}$)	0.85 – 233.18	0.65 – 158.98
Mean discharge ($m^3\ s^{-1}$)	3.81	4.11
CV of mean discharge (%)	198.51	189.56

Table 6.5: Hydrological characteristics of the Esk catchment monitored at Grosmont

6.3.2 Annual Suspended Sediment Transfer

The average SSC for this monitoring period is 24.87 mg L^{-1} with a coefficient of variation of 213.22%, highlighting a great amount of variability during the year. The maximum SSC was measured during a storm event on 16th July 2009, where it peaked at 953.19 mg L^{-1}. During the 2007/08 and 2008/09 water years, the SSCs vary from 0.09 – 889.64 mg L^{-1} and 1.54 – 953.19 mg L^{-1} respectively. The mean SSCs for each year are 26.13 and 24.05 mg L^{-1} with associated CVs of 208.17 and 216.73%.

Again, there is a considerable scatter between observed SSCs and discharge. However, this is somewhat reduced compared to that observed at the monitoring station at Danby. Here, river flow is a dominant driver of SS flux, although variability in the relation may occur as a product of SS availability in the catchment. The relation between the two variables is demonstrated in Figure 6.5.

Despite the scatter in the developed rating relationship for each period, the relationships are highly statistically significant ($P < 0.001$) with explained variance of 68.0% and 52.8%. Following bias correction, relative errors are in the region of -7.17 and 13.26% (Table 6.6). In this case, the rating coefficients between the periods are dissimilar. There is a greater availability of sediment at low discharges during the 2008/09 hydrological year; however, during 2007/08, the SS response to increasing discharge is abrupt and steep resulting in the generation of a b-coefficient of 1.21, compared to 0.93 derived from year one data. However, the lack of two complete hydrological years' data means the Q-SSC relationship described above may not be representative of the processes occurring across the entire hydrological year.

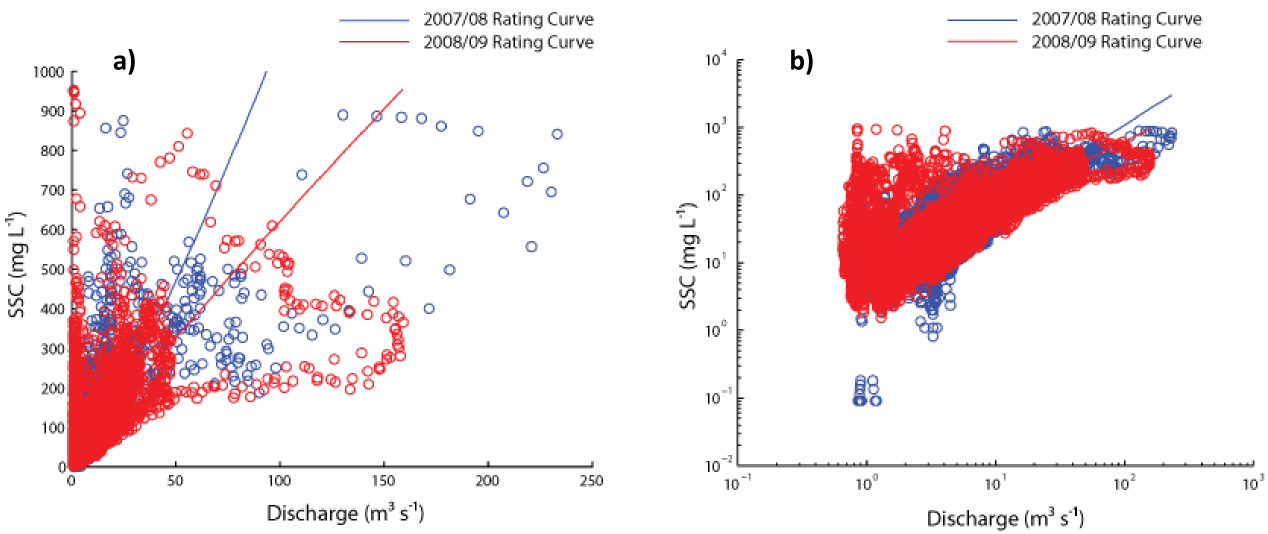


Figure 6.5: Annual sediment rating curves at Grosmont, river Esk in **a)** normal space and; **b)** log space.

Table 6.6: Summary of annual sediment loadings and annual sediment rating curve parameters at Grosmont, river Esk

	n	Sediment Load (t)	90% transported in...	*a*	*b*	Log-normally distributed error	Coefficient of Determination (R^2)	*P*	Relative error of Estimation (%)	Duan (1983) correction factor	Relative error of estimation (%) After SF
2007/08	35136	8621.0 (± 957.79)	23.43%	3.9240	1.2093	0.0638	0.6804	*< 0.001*	-11.8244	1.0528	-7.1708
2008/09	33471	10 044 (± 1115.9)	13.17%	5.3687	0.9295	0.0867	0.5280	*< 0.001*	-29.1917	1.5995	13.2611

Following the integration of simultaneous river flow and SS measurements, the SS loads were calculated for the partial 2007/08 and 2008/09 water years. The SS loads calculated during years one and two are not directly comparable given that data are available for 65% and 82% of each hydrological year respectively. In the first sampling year, it is estimated that 8621.0 (± 957.79) t of fine sediment was transported through the river reach equating to a sediment yield of 30.08 (± 3.34) t km^{-2}. During the second sampling year, 10 044 (± 1115.9) t of fine suspended sediment was transferred, equating to 35.05 (± 3.89) t km^{-2}. When these loads are scaled up to a full year, the annual load would be 13 263.0 t yr^{-1} (46.28 t km^{-2} yr^{-1}) and 12 249.0 t yr^{-1} (42.74 t km^{-2} yr^{-1}) although this assumes that the monitored period is representative of the full year and missing period, which may not be a valid assumption. During this monitoring period, minimal transfer occurs under low-flow conditions. This is highlighted by 90% of the total suspended sediment load being transported in 23.43% of time for the first year which falls to 13.17% during the second year (see Table 6). This highlights that the infrequent, highly erosive events at the Danby sub-catchment scale are not quite as important in contributing to the total suspended sediment load at the Grosmont catchment scale.

6.3.3 Monthly and Seasonal Variability in Suspended Sediment Transfer

Within and between seasons, strong monthly fluctuations in the fine suspended sediment transfer occur, which are largely a function of the total monthly water yield. At the Grosmont station the mean monthly suspended sediment load is 933.36 tonnes (CV = 130.64%). An overview of the monthly transfer of water yield and suspended sediment loads can be seen in Figure 6.6.

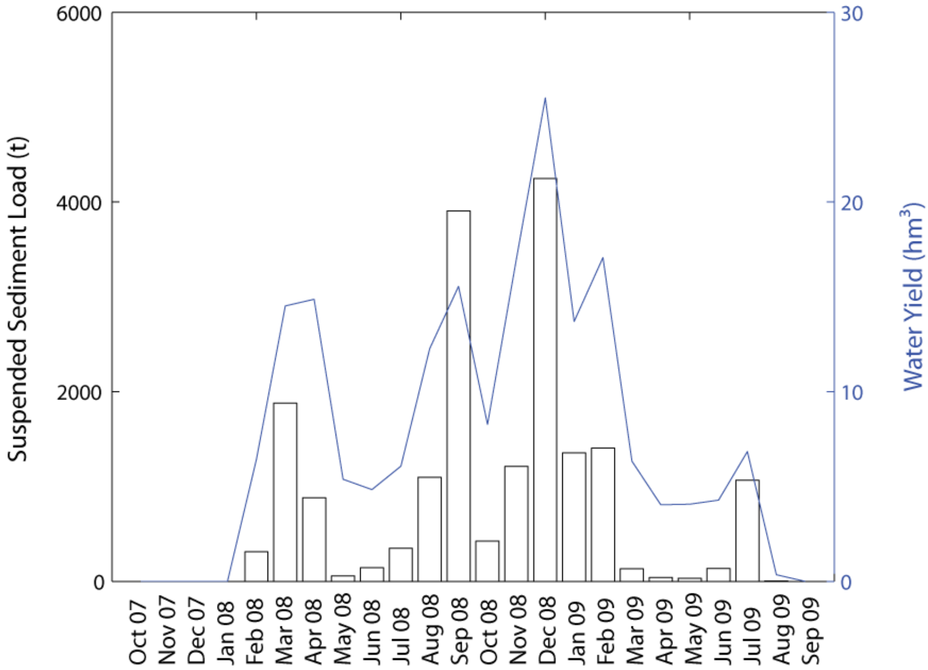


Figure 6.6: Monthly suspended sediment load (t) and water yield (hm^3) at Grosmont, river Esk

The seasonal SS loads vary through the monitoring period with the SS load during spring 2008 contributing 2752.5t whereas in the following year, only 178.4t of fine SS is transferred. Summer and autumn 2008 are responsible for the largest proportion of fine sediment transfer, transporting 5341.5 and 5872.3 t respectively. The seasons with the highest suspended sediment loads (Summer 2008 and Autumn 2008) also contain the two largest individual monthly suspended sediment loadings. These are December 2008 (4246.0 t) and September 2008 (3906.4 t). However, October 2007 – January 2008 and August – September 2009 are not adequately represented in the record.

The relationship between monthly water yields and SS load reveals periods of the year where there is a relative depletion and also abundance of fine sediment available for transfer. These periods can be picked out visually and through the analysis of the multiple hysteresis loops of varying strengths, complexity and directions (Figure 6.7). Year one, which represents the 2007/08 hydrological year shows one distinct hysteresis loop. This hysteresis is clockwise in direction and relatively strong. In February 2008 water yield is quite low (6.43 hm^3), along with total load (310.13 t). In March, increases in water yield are mirrored with increases in the total load. This represents the peak in the hysteresis loop with a water yield of 14.52 hm^3 and sediment load of 1879.9 t. In April, the water yield remains high at 14.89 hm^3. However, there is a 46% reduction in the suspended load. This relative depletion of suspended sediment load continues throughout May and June. An exceptionally high relative suspended sediment load found in September is also observed. This hysteresis behaviour is very similar to that found at the Danby sub-station, which highlights a period of relatively enriched sediment sources which is then subsequently depleted. However, the period spanning October – January 07 is not represented in the record which may hide further evidence of monthly hysteresis in the catchment.

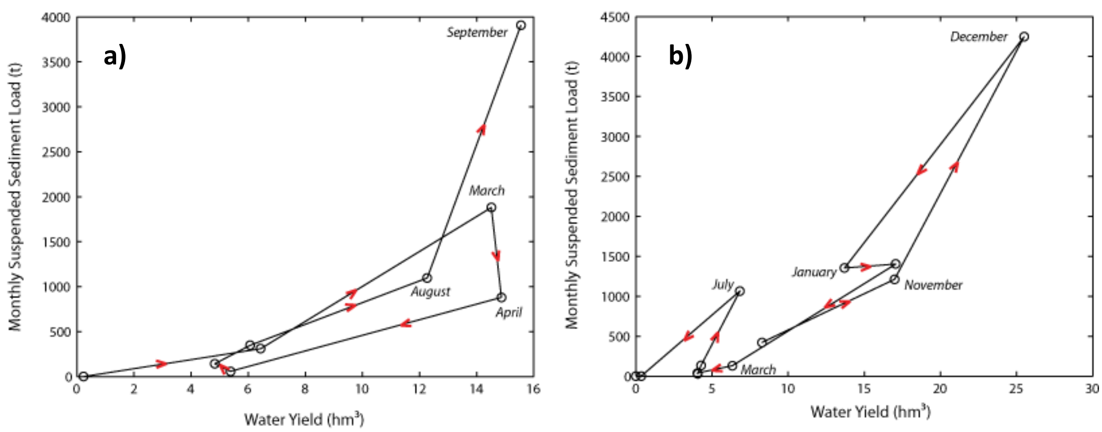


Figure 6.7: Monthly water yield and sediment load hysteresis patterns at Grosmont, river Esk during the **a)** 2007/08 and; **b)** 2008/09 hydrological years.

During the 2008/09 hydrological year, a similar relationship between monthly suspended sediment loads and water yields is observed. The first evidence of hysteresis occurs at the beginning of the 2008/09 hydrological year. In October, both the water yield and sediment load are low (8.27 hm^3 and 422.46 tonnes respectively). The water yield and sediment load then increase during the subsequent months of November and December 2008, when the peak in both total water yield and sediment load are reached (25.49 hm^3 and 4246.0 tonnes respectively). In January, the water yield decreases substantially (13.70 hm^3), which despite being 19% less than that in November, produces a suspended sediment load 14% greater, producing the anti-clockwise hysteresis shown in Figure 6.7. Following this, the total water yield increases to 17.01 hm^3. However, the total sediment load only increases slightly by 50.85 t. This illustrates the potential for sediment stores being relatively depleted in November 2008, with January 2009 and to a lesser extent February 2009 being periods of relative abundance. A period of low flow follows between March and June (4.06 hm^3 – 6.33 hm^3). However, a slight increase in water yield in July (6.83 hm^3) is met with a disproportionate increase in total sediment load (1066.6t), which is over 8 times greater than that measured in April when total water yield was a comparable 6.33 hm^3. This period of relative enrichment is also observed in the Danby sub-catchment of the Esk basin. The months of August – September 09 are not adequately represented in the record which may hide further evidence of monthly hysteresis in the catchment.

In order to further better understand variations in sediment transfer in the catchment, additional analysis involving development of seasonal rating curves was conducted. The parameters of these models, along with statistical summary information are provided in Table 6.7.

	Sediment Load (t)	*a*	*b*	Log-normally distributed error	Coefficient of Determination (R^2)	*P*	Relative error of Estimation (%)	B*	Relative error of estimation (%) After SF
Autumn 07[b]	---	---	---	---	---	---	---	---	---
Winter 07/08[a]	510.6	3.42	1.3103	0.0523	***0.64***	< 0.001	-22.4507	*1.1837*	-8.2035
Spring 08	2752.5	2.70	1.2815	0.0390	***0.81***	< 0.001	-18.6081	*1.1306*	-7.9764
Summer 08	5341.5	5.56	1.1728	0.0651	***0.69***	< 0.001	4.7422	*N/A*	4.7422
Autumn 08	5872.3	3.19	1.2043	0.0330	***0.81***	< 0.001	2.9641	*N/A*	2.9641
Winter 08/09	2904.4	2.73	1.3277	0.0291	***0.80***	< 0.001	-5.9712	**1.0411**	-2.1095
Spring 09	178.4	4.37	1.1336	0.0456	***0.36***	< 0.001	-18.5446	*1.1559*	-5.8449
Summer 09[b]	---	---	---	---	---	---	---	---	---

Table 6.7: Summary of seasonal suspended sediment transfer at Grosmont, river Esk. * Duan (1983) in italics, Kao (2005) in Bold, *N/A* represents periods where no correction factor was applied. [a] Data during Winter 07/08 began on 30th January and so is not a complete season. [b] No monitoring data is available for these periods which is highlighted by the ---.

Analysis of the seasonal rating coefficients developed for the Grosmont monitoring station indicates that a depletion in available sediment under low-flow conditions (minimum a-coefficient) occurs during winter 2008/09. Winter 2007/08 and 2008/09 are also periods when SSCs respond most sensitively to increases in flow, as represented by maximum b-coefficients of 1.3277 and 1.3103 for 2007/08 and 2008/09 respectively. In the first year, this season represents a period of low flux (510.6 t) but the period of highest flux in the second year (2904.4 t). This highlights the importance of considerable flow events in the transfer of fine sediment and the lack of transport under low flow conditions during this period.

Conversely, the summer months of 2008 (June 21st – September 20th) represent a period of enhanced sediment availability under low-flow conditions, readily mobilisable fine sediment in the catchment (maximum a-coefficient of 5.56), which also has a relatively dampened response to increasing flow (second smallest *b* coefficient value of 1.1728). In 2008, this is also a period of high sediment transfer with 2124.6 t of fine sediment being transferred. The hysteresis pattern at this time also appears to represent a period of enhanced sediment availability. These findings at the Grosmont monitoring station are comparable to those found at Danby.

Similar to Danby, analysis of the relationship between the rating coefficients demonstrates a negative linear relationship. However, this is not significant (R^2 = 0.54; p = 0.095). This again highlights that the inconsistencies in the sediment yield processes under different flow conditions that have been identified in the Danby sub-catchment are also in operation at the larger catchment at the Grosmont monitoring station with a complex control over sediment production and delivery between seasons throughout the Esk valley. These complexities will now be examined in further detail through analysis of the within storm fine sediment dynamics.

6.3.4 Within Storm Sediment Dynamics

6.3.4.1 Importance of Infrequent Events

The analysis of seasonal and monthly fine-sediment flux dynamics has highlighted time periods of the year which are responsible for the transfer of fine suspended sediment in the Esk catchment above the Grosmont monitoring station. As was has been demonstrated at the Danby monitoring station, there is often a large amount of variability in the timing of fine sediment transfer, with a substantial mass of sediment often being transported in a very short period of time. This is exemplified by 3789.4 t of sediment being transported in a single event lasting less than two days during December 2008. This mass of sediment accounted for 89% of the monthly load and 38% of the annual load. Given the importance of these individual events, this section examines event-based fine-sediment dynamics. Events were defined visually from event hydrographs where a marked increase in discharge occurred. In the case of consecutive events, these were treated as separate events where flow recession produced a distinct trough between events. 66 sediment transfer events were recorded at the Grosmont monitoring station.

6.3.4.2 Hydro-meteorological Controls on Event Flux

As with the Danby monitoring station, the extent to which the event suspended sediment load (tonnes) was related to; (a) peak event discharge (m^3 s^{-1}); (b) event max rainfall intensity (mm hr^{-1}); (c) event rainfall total (mm) and; (d) antecedent rainfall total (mm over previous 5 days) was examined. This was achieved through the production of a scatter plot matrix and linear regression analysis. This highlighted that the peak discharge was the main descriptor for the variation in event suspended sediment loads (R^2 = 0.96; p < 0.001), with the relationships for total rainfall amount (mm), rainfall intensity and antecedent conditions being statistically insignificant. Furthermore, analysis of the ability of the meteorological variables to predict peak discharge was very poor. It is perhaps unsurprising that the limited meteorological instrumentation does not capture the spatial heterogeneity of rainfall across this meso-scale catchment. Therefore, further analysis of the way in which these meteorological variables are related to suspended sediment dynamics is abandoned due to concerns over process representation.

6.3.4.3 Assessment of Event Hysteresis Patterns

Visual examination of the pattern of hysteresis was conducted on the 66 flow events, the summary of which is provided in Table 8. The data demonstrate that clockwise hysteresis events dominate the record, accounting for 45% of the total number, producing an median event load of 139.81 t with a MAD of 111.12 t. These events transfer a total of 14 293t of fine suspended sediment, which equals 80.2% of the total load transferred. Events displaying nearly no hysteresis account for 30% of events and transfer a total of 1269.5t of fine sediment. This accounts for 7.1% of the event total load. The median event load for this class is 27.67 t, with a MAD of 14.95 t. This group is associated with relatively small magnitude events, with the largest event transferring only 228.76t. Given that the no-hysteresis group is often associated with a lack of depletion and continual sources, this finding adds credence to the notion that during lower-magnitude events, the sediment flux is governed by flow capacity (transport-limited), whereas during larger events, erosional processes and sediment availability become the dominant control (supply-limited). Events displaying anti-clockwise hysteresis occur 18 times. This equates to 27% of the total but only 13% of the total event load. This event type produces moderately sized sediment loads with a median event total of 42.93 t with a relatively low MAD of 28.68 t. The final two events are classified as figure-of-eight with a clockwise loop. These events occur during small events, transferring a meagre 1.59t and 24.1t of fine sediment.

Hysteresis Condition	*Number*	*Median Event Load (t)*	*Median Absolute Deviation (t)*
Clockwise	30	139.81	111.12
Anti-clockwise	18	42.93	28.68
Figure of Eight (anti-clockwise loop)	0	---	---
Figure of Eight (clockwise loop)	2	12.85	11.26
Nearly none	20	27.67	14.95

Table 6.8: Summary of hysteresis patterns observed at Grosmont, river Esk

Of note is that there are some extremely large events that were observed during this monitoring campaign, which produced event sediment loads of 3789.4t and 3637.0t and exhibited clockwise hysteresis (Figure 6.8). Together, these account for 52% of the total load transported during events

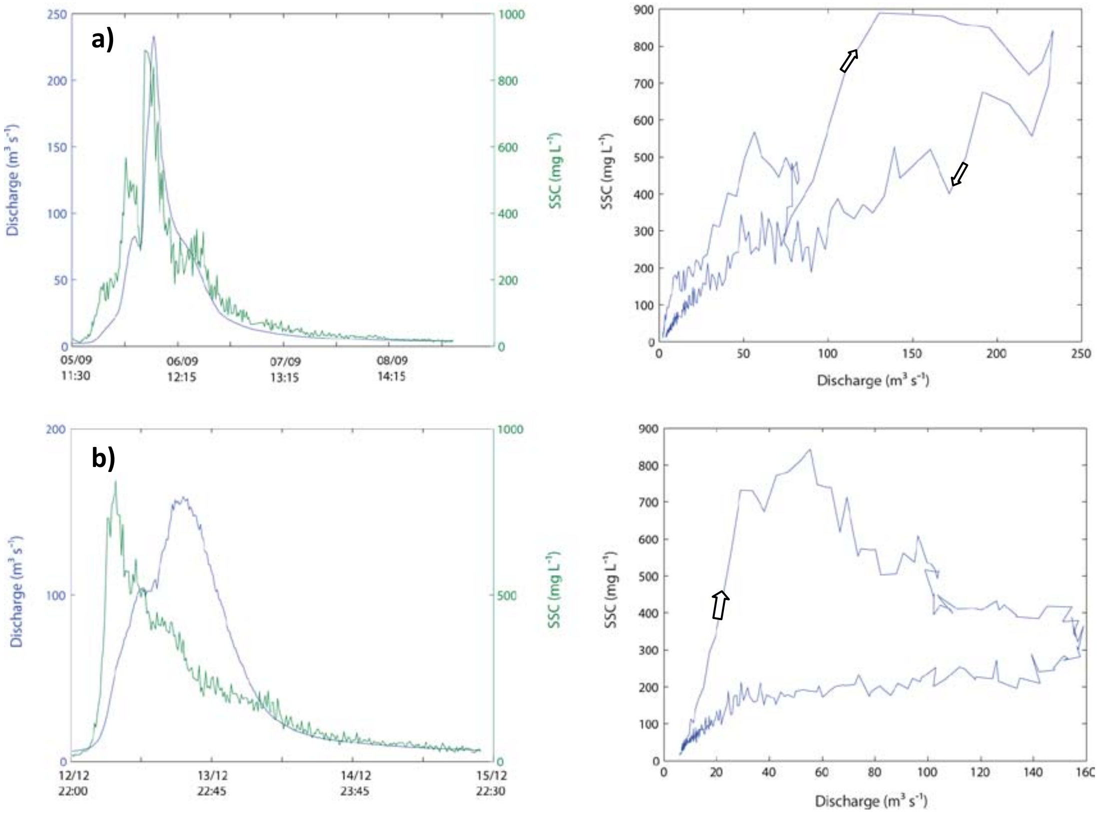


Figure 6.8 (a) Clockwise hysteresis pattern produced during a multi-peaked event during September 2008 and; **(b)** Large event producing a considerable clockwise hysteresis loop during December 2008 at Grosmont, River Esk

Subsequent analysis using the Wilcoxon-Mann-Whitney-U non-parametric test for differences in event median loads for each hysteresis condition has identified that there are significant differences in the values between clockwise events and anti-clockwise (P = 0.02), figure-of-eight (clockwise loop) (P = 0.05), and nearly no hysteresis (P < 0.001). Similar to the findings at the Danby monitoring stations, clockwise events absolutely dominate the transfer of fine suspended sediment. No other statistically significant differences are found for the total load transferred between the other hysteresis conditions.

6.3.4.4 Quantitative Assessment of Event Hysteresis Patterns

Having determined the occurrence events displaying various patterns of hysteresis and the conditions, under which they occur, a quantitative assessment their magnitude and direction is carried out and the potential for these attributes to be predicted by hydrological variables is also assessed. Following calculation of the hysteresis index proposed by Lawler *et al* (2006), descriptive statistics for the events are calculated. There are a total of 40 positive and 26 negative events which further illustrates the dominance of events with greater SSCs on the rising limb of the hydrograph. The mean and median index values are both positive, with values of 0.174 and 0.160 respectively, with a range spanning from -9.6812 to 3.9545. These two extreme hysteresis events can be seen in Figure 6.9. The standard deviation is 1.5786, signifying a considerable variability in the HI values.

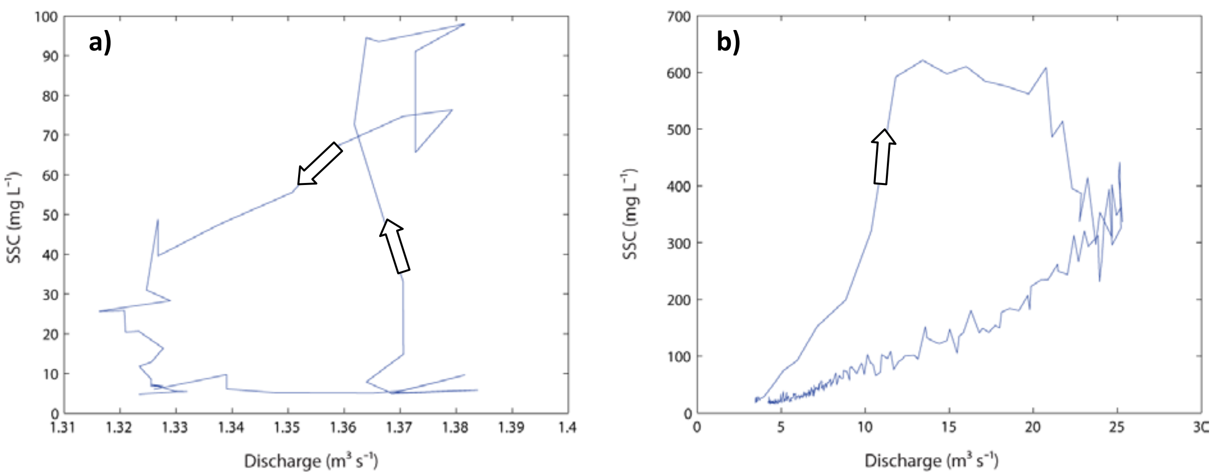


Figure 6.9 (a) Minimum HI event on 4th December 2008 with a value of -9.68 and; **(b)** Maximum HI event on 19th January 2009 with a value of 3.95 at Grosmont, river Esk

Following partitioning of the dataset into positive and negative classes, a Wilcoxon-Mann-Whitney non-parametric test was conducted to test for differences between the negative and positive groupings for mean suspended sediment loads. Statistically significant differences between the groups were obtained (P = 0.0015). The median load of positive events is 88.38 t (MAD = 74.18 t) and the median load for negative events is 33.84 t (MAD = 21.12 t). It is clear from this analysis that events displaying positive hysteresis transfer a greater mass of fine sediment than events displaying negative hysteresis. However, unlike at Danby, the HI values cannot be predicted using the event hydrological variables, highlighting more complex controls on the direction and magnitude of hysteresis with hydrological connections being less pronounced lower in catchment.

6.3.5 Section Summary

(1) In the 2007/08 and 2008/09 hydrological years, the SSCs vary from 0.09 – 889.64 mg L^{-1} and 1.54 – 953.19 mg L^{-1} respectively. The mean SSCs for each year are 26.13 and 24.05 mg L^{-1}.

(2) For the 2007/08 and 2008/09 hydrological years, data are available for 65% and 82% of each year respectively. The scaled-up annual loads are 13 263.0 t yr^{-1} and 12 249.0 t yr^{-1}, equating to 46.28 t km^{-2} yr^{-1} and 42.74 t km^{-2} yr^{-1} respectively.

(3) Simple rating curves are able to predict SSCs from discharge measurements, providing a useful means of estimating flux at this location in the short-term where only Q data exists.

(4) Within and between seasons, strong monthly fluctuations in the fine suspended sediment transfer occur, which are largely a function of the total monthly water yield although some hysteresis is observed. Periods of highest SS transfer occur in summer and autumn 08 and winter 08/09.

(5) The efficiency of rating curve predictions can be improved by developing seasonal models. Analysis of the seasonal rating curve parameters highlights relative sediment source depletion under low-flow conditions during winter 2008/09. SSCs respond most sensitively to increases in flow during Winter 2007/08 and 2008/09.

(6) Regression analysis between the *a* and *b*-coefficients has highlighted the inconsistencies in the sediment yield processes at varying times of the year.

(7) Peak event discharge is a very good predictor of event sediment load ($R^2 = 0.96$; $P < 0.001$). Meteorological variables are poor predictors.

(8) Clockwise hysteresis events are the most frequent (45 %) and transport the vast majority of fine sediment (80.2 %). Extremely large clockwise events observed produced event sediment loads of 3789.4t and 3637.0t. Clockwise events produce a median load 3.26 times greater than that of anti-clockwise events. Differences are found between median loads of clockwise events and anti-clockwise (P = 0.0186), figure-of-eight (clockwise loop) (P = 0.0471), and nearly no hysteresis (P = 0.001).

(9) Meteorological conditions fail to explain the non-linear relationship between flow and SSC.

(10) Statistically significant differences between negative and positive groupings for median suspended sediment loads were obtained with higher values for the positive events. Hydro-meteorological variables are not effective predictors of the magnitude of hysteresis observed.

6.4 Multiple Scale Sediment Transfer Dynamics

6.4.1 Temporal Lags in Suspended Sediment Concentrations and Flow between the Danby and Grosmont, River Esk

Firstly, the lag between the SSCs and discharge measurements made at the Danby and Grosmont monitoring stations on the main Esk River was assessed. This was achieved through the assessment of the cross-covariance between the signals generated at each station. This is a measure of the serial correlation between the two variables (Singer and Dunne, 2001). The number of frames needed to shift for maximum covariance is obtained, along with the associated Pearson correlation coefficient and *P*-value after the shift (Table 6.9). The comparative strength of the covariance signal also provides information about the stability of the temporal lag.

	n lags	*Pearson correlation coefficient*	*P value*
Q	2	0.90	< 0.001
SSC	1	0.68	< 0.001

Table 6.9: Results of cross-covariance for SSC and Q at Danby and Grosmont, River Esk

For both series a very strong covariance signal is obtained when the data at Danby is shifted two frames (30 minutes) forward for the flow series and one frame (15 minutes) forward for the SSC data-series (Figure 6.10). The shift required to obtain the greatest covariance is similar for both data series. Both series have a strong association between the variables, with correlation coefficients highly significantly different from zero ($P < 0.001$). The lower correlation coefficient for the SSC data series is not unusual given the potential for deposition and entrainment of new material from the lower reaches of the catchment.

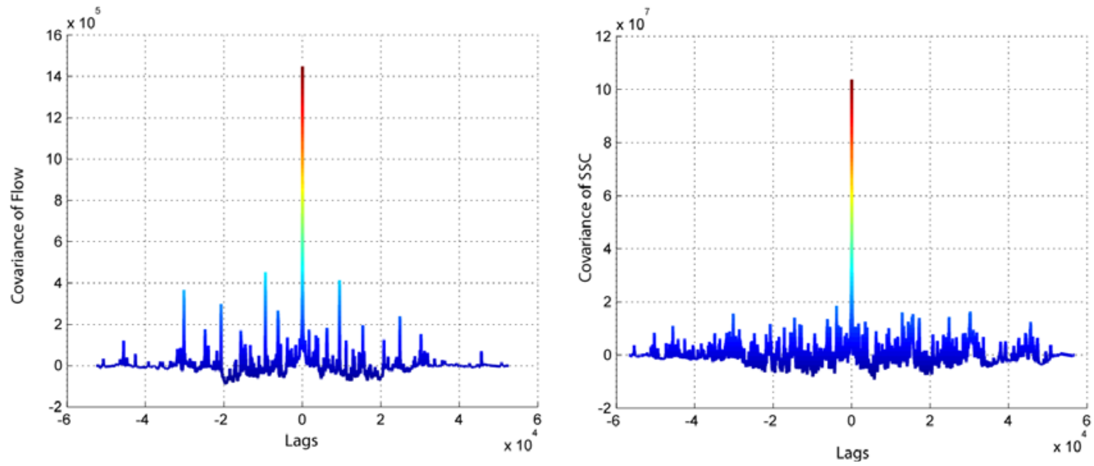


Figure 6.10: Output from the cross-covariance analysis of **a)** flow and **b)** SSC between the Danby and Grosmont, River Esk

6.4.2 Spatial Variability in the Importance of Infrequent Event Contributions

This research has already demonstrated that fine suspended sediment in the Esk catchment is highly episodic, with 90% of the average annual load at Danby and Grosmont occurring in 6.7% and 23% of the total time respectively. The importance of extreme events being responsible for high suspended sediment loads has long been recognised (Wolman and Miller, 1960). When the ten largest events at the sub-catchment and catchment scales are extracted, they account for 7050.2.7t of sediment at the sub-catchment scale and 13085.1t at the catchment scale. This equates to 64.3% and 70.1% of the total mass of sediment transferred through each of these locations. The contribution of these largest 10 events to the total suspended load is comparable to recent research conducted by Gonzalez-Hidalgo *et al.* (2010) who found that upon the analysis of suspended sediment load data across 1314 catchments in the USA, the largest ten events on average accounted for 61% of the total load. However, the fact the largest ten events at the Grosmont station contribute a greater proportion to the total load compared to the Danby station suggests that sediment export during the largest events is greater per unit area at the catchment scale, highlighting the continued production of erodible material available for transfer during high magnitude events as distance from the steep headwater increases. This contradicts Gonzalez-Hidalgo *et al.* (2010) who found that the contribution of the largest 10 events to the long term sediment load decreased with increasing catchment size. However, their analysis was based on a data set consisting of over 2 500 000 daily events and over 10 000 days' worth of data, which may explain the conflicting findings of this research, which ultimately may not be representative of the long-term flux in the Esk catchment.

6.4.3 Spatial Variability of Event Hysteresis Dynamics

The assessment of event hysteresis at the Danby and Grosmont monitoring stations separately has highlighted the dominance of clockwise hysteresis at both the sub-catchment and catchment scales, indicating the presence of fine suspended sediment sources proximal to the channel throughout the whole of the Esk catchment. Despite this dominance throughout, the hysteresis patterns at Grosmont appear to be more complex and driven less by the hydrological characteristics of the event. Rather, it seems that the timing of tributary inputs and areas of sediment availability in the lower catchment may be of greater relative importance. Further analysis is therefore conducted to quantify the difference in the response at these two scales.

Upper and lower catchment runoff events were identified where the river discharge at the Grosmont station responded within 24 hours of the start of an event at the Danby monitoring station. A total of 47 paired events were matched and selected for analysis. Unsurprisingly, the event suspended sediment loads at the sub-catchment and catchment have a strong positive linear relationship ($y = 2.3x-10$; $R^2 = 0.85$; $P < 0.001$). Initial analysis of the paired hysteresis patterns through comparisons of the calculated HI between sites shows a lack of a statistically significant relationship between the sub-catchment and catchment scale. However, a more detailed examination, whereby the hysteresis patterns are examined on an individual event basis through the calculation of the Similarity Function (SF) allows the relative similarity of hysteresis patterns between two sites to be compared. However prior to its calculation, the paired samples were checked for comparable orientation and hysteresis classification since conflicting shapes and/or typologies cannot be directly compared using this method. Paired events which failed to meet this limitation were omitted from analysis. The SF for the dataset ranged from 1.9024 (most similar) to 0.4323 (least similar), with a mean value of 1.3169 (CV = 23.28%). This mean value is high, especially given that the compiled dataset consists of many low magnitude events, during which, the sediment is likely to be sourced from limited areas of the catchment thereby potentially leading to complex SSC-Q patterns between sites. Figure 6.11 demonstrates a range of paired events analysed along with their calculated SF value with the most similar at the top left, scaling to the least similar at the bottom right. Given the large number of matched events, interpretation of the controls on pattern similarity is complicated by the number of events which are insignificant in terms of the annual fine sediment load. Therefore, the largest ten sediment transfer events were extracted for further analysis with summary information provided in Table 6.10.

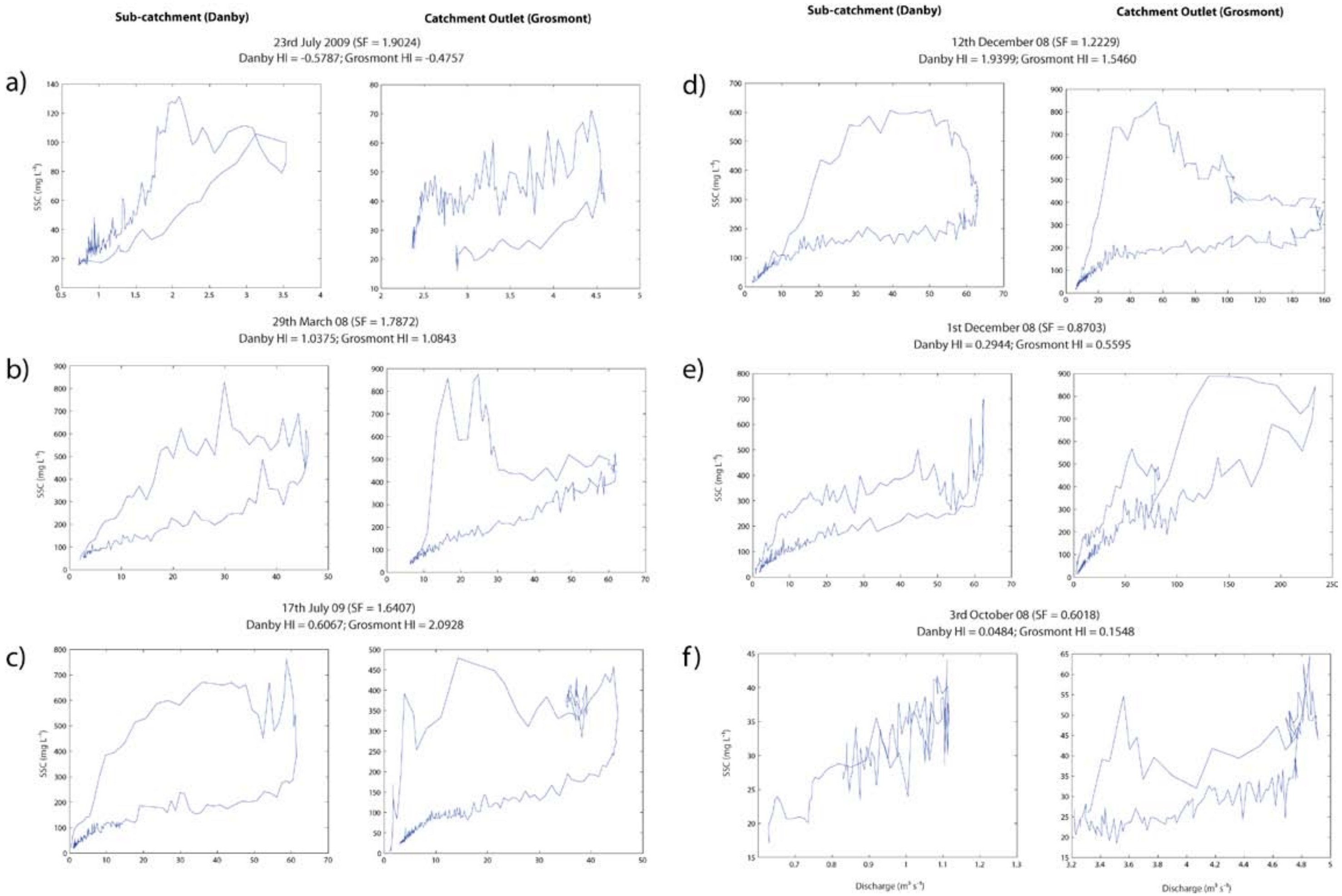


Figure 6.11: Range of Similarity Function values obtained through analysis of paired events at the river Esk monitoring stations at Danby and Grosmont

Event Start	Danby Peak Discharge ($m^3 s^{-1}$)	Danby SSL (t)	Grosmont Peak Discharge ($m^3 s^{-1}$)	Grosmont SSL (t)	Event SF	Danby Rainfall Total (mm)	Danby Max Rainfall Intensity (mm hr^{-1})	Danby Antecedent Rainfall (5 days) (mm)
1st December 08	62.53	1215.2	233.2	3789.4	0.8703	---	---	---
12th December 08	63.07	1341.9	159.0	3637.0	1.2229	19.8	2.8	13.5
29th March 08	46.12	768.1	62.0	1295.4	1.7872	23.2	3.4	9.2
15th February 09	25.57	288.8	46.8	1079.6	1.2472	---	---	---
17th July 09	61.36	951.8	45.2	912.8	1.6407	32.4	5.8	5.6
22nd January 09	33.21	478.0	47.8	710.5	1.5755	14.2	2.6	29.0
8th November 08	19.24	158.5	27.0	486.8	1.6248	11.8	5.4	15
19th August 08	33.02	324.5	31.0	407.3	1.7777	19.6	1	15.4
19th January 09	17.91	194.8	25.3	404.2	1.5893	22.0	5.6	12.2
2nd November 08	23.51	243.1	26.4	362.1	1.5824	20.4	3.2	13.2

Table 6.10: Flow, sediment loading, meteorological and SF data for the ten largest matched suspended sediment transfer events at Danby and Grosmont, River Esk. --- Represents no available meteorological data available for this event

Following analysis of these high magnitude events, it is clear that the associated similarity functions are high, with a mean value of 1.49. To put this into context, the largest SF value observed by Smith & Dragovich (2009) was 1.44 which suggests a high degree of similarity in sediment flux response between the Danby and Grosmont monitoring stations.

The extent to which hydro meteorological variables contribute to the similarity of paired SSC-Q hysteresis patterns (as quantified by the SF) were then determined through regression analysis. Of the independent variables assessed for relationships with the SF index, none of the meteorological variables, or peak discharge and SS load measured at Danby produced correlations which were significant. However, the suspended sediment load (t) and the peak discharge (m^3 s^{-1}) measured at the Grosmont station were found to be strongly correlated with the event SF (Figure 6.12). Of interest is that the correlations developed for each of the two significant variables are strongly negative. This suggests that it is the events of moderate magnitude events which are most similar; with some of the more intense events producing SFs which are relatively low.

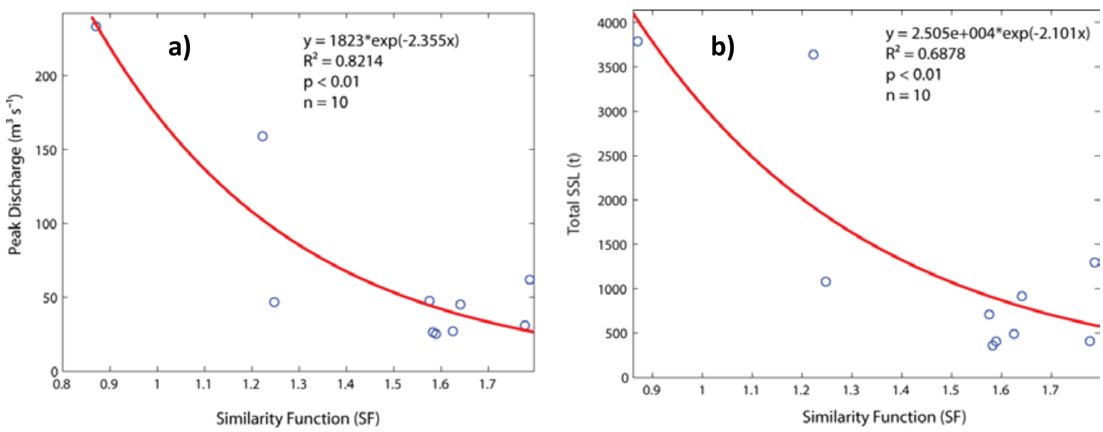


Figure 6.12: Regression analysis of the SF and the **(a)** peak discharge at the catchment outlet and the **(b)** total suspended sediment load at the catchment outlet

The two largest suspended sediment transport events have the two smallest SF values. During these events, it is the timing of water reaching the main River Esk which results in the dissimilar event responses between the Danby and Grosmont monitoring stations. This is caused by a complex hydrograph at Grosmont, whereas at the sub-catchment of Danby, the hydrograph has a single peak (Figure 6.13) This systematic variability in the complexity of hydrographs at varying spatial scales in a catchment is not uncommon (Rinaldi and Darby, 2008) and is likely to be a consequence of rainfall heterogeneity across the 287 km^2 catchment and the timing of tributary inputs across the lower catchment resulting the generation of a more complex hydrograph. This phenomenon has also been observed previously by Asselman (1999) and Rovira & Batalla (2006).

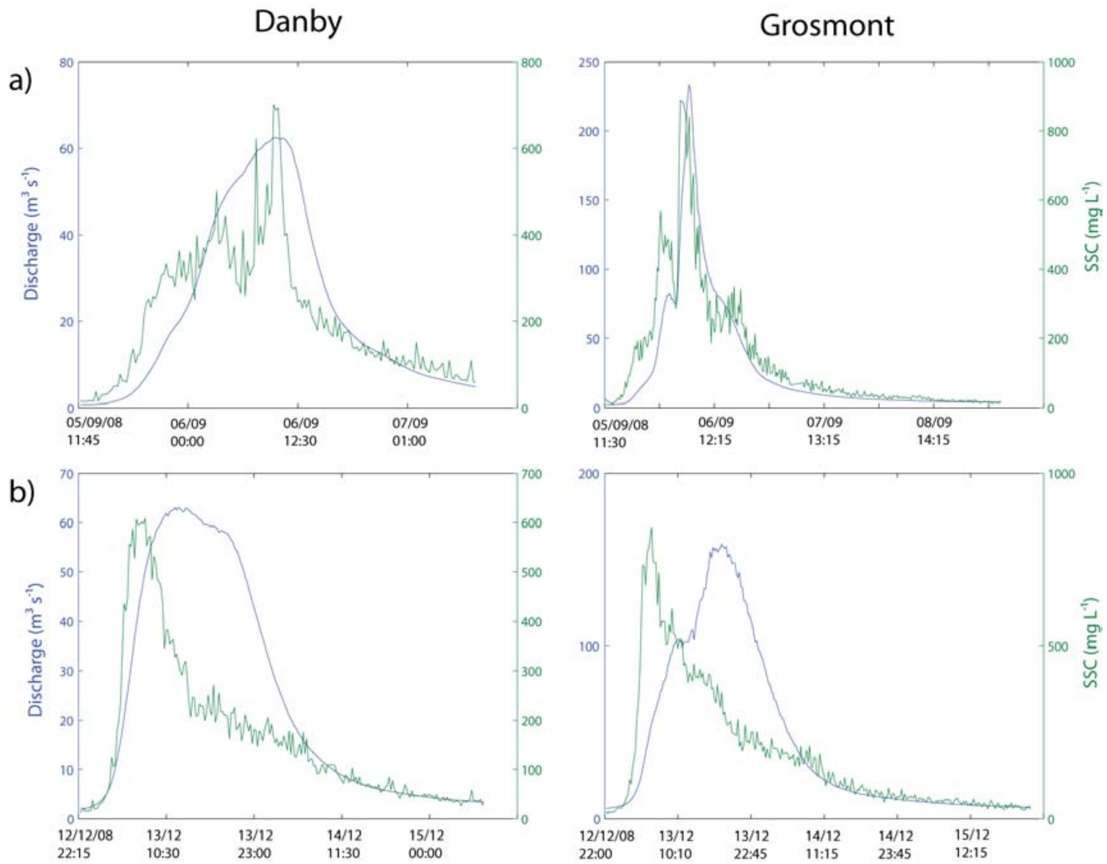


Figure 6.13: A comparison of the flow and SSC responses for events beginning on **a)** 5th September 08 and; **b)** 12th December 08. These events produce the lowest similarity functions of the 10 largest events

For the events which are not subject to this hydrograph complexity, the SF value is considerably higher which is a reflection of the continuity of erosion and sediment transfer processes in across the catchment, although the magnitude of response between the sites may differ (as a result of input volumes), the overall hysteresis pattern is comparable. There are two scenarios where this phenomenon may occur:

(a) Homogenous rainfall and erosion processes across a catchment resulting in the synchronous timing of flow peaks and sediment delivery from tributaries of sub-catchments adding to the response at the catchment outlet. In this scenario, the processes responsible for the movement of sediment are well distributed throughout the catchment. This may be known as the 'widespread event scenario'.

(b) Spatially localised rainfall in the monitored sub-catchment may produce a sufficiently large suspended sediment signal which is transmitted through as far as the catchment outlet. Although, in this case, the signal will be severely dampened at the catchment outlet.

In the case of the Esk catchment, the increase in both water yield and suspended sediment load contributions downstream of the Danby monitoring station appears to largely discount the phenomenon of spatially localised rainfall events producing the largest suspended sediment transfer events, rather it seems much more likely that the observed similarities are driven by the mobilisation and transfer of sediment from sources distributed throughout the catchment. Given that analysis of within-storm sediment dynamics points towards the importance of sources proximal to the channel, it seems probable that the within-channel deposits and bank materials are readily mobilised during these large magnitude events.

6.4.4 Section Summary

(1) Strong covariance signal between Danby and Grosmont with lags of 30 minutes and 15 minutes for Q (R^2 = 0.90) and SSC (R^2 = 0.68) measurements.

(2) Highly episodic transfer at Danby and Grosmont with 90% of the average annual load at occurring in 6.7% and 23% of the total time respectively.

(3) The ten largest events at Danby and Grosmont account for 7050.2.7t and 13085.1t respectively. This equates to 64.3% and 70.1% of the total mass of sediment at each of these locations. Sediment export is greater per unit area at Grosmont for these largest events, highlighting the continued production of erodible material available for transfer during high magnitude events.

(4) Strong linear relationship between event loads measured at Danby and Grosmont (R^2 = 0.85; $P < 0.001$).

(5) Mean SF of all events of 1.32 and largest ten of 1.49, highlighting very similar hysteresis responses between Danby and Grosmont. The two largest sediment transport events have the two smallest SF values. This is due to hydrograph complexity at Grosmont.

6.5 Broadway Foot Suspended Sediment Dynamics

Monitoring of water level and SSC at Broadway Foot on the River Rye began on 22nd July 2008 and continued until 8th October 2009, providing over one year's complete monitoring data. Sampling during the first hydrological year was limited to two full months and as such is not representative of the annual dynamics; however, results are included for completeness. The second hydrological year (2008/09) was successfully sampled throughout.

6.5.1 Hydrology

Over the course of the monitoring period the total water yield was 88.92 hm^3 with discharge ranging from 0.54 to 55.0 $m^3 s^{-1}$, with the maximum discharge occurring during a storm on the 13th December 2008. The mean value over this period is 2.36 $m^3 s^{-1}$ with a coefficient of variation of 159.56%. In the 2008/09 hydrological year the annual water yield was 71.98 hm^3 with a range in discharge of 0.54 – 55.00 $m^3 s^{-1}$. The mean discharge was 2.25 $m^3 s^{-1}$ with a coefficient of variation of 166.28 %.

	2008/09
Water yield (hm^3)	71.98
Flow range ($m^3 s^{-1}$)	0.54 – 55.0
Mean discharge ($m^3 s^{-1}$)	2.25
CV of mean discharge (%)	166.28

Table 6.11: Hydrological characteristics of the complete 2008/09 hydrological year in the Upper Derwent catchment at Broadway Foot on the River Rye

6.5.2 Annual Suspended Sediment Transfer

The average SSC for this monitoring period is 15.36 mg L^{-1} with a coefficient of variation (CV) of 269.85%, highlighting a great amount of variability during the year. The maximum SSC was measured during a storm event on 23rd June 2009, where it peaked at 828.69 mg L^{-1}. The between year variability in SS transport is quite limited. In the complete 2008/09 hydrological year, the SSC ranges from 0 0.02 – 828.69mg L^{-1}. The mean SSC is 13.87 mg L^{-1} with a CV of 281.61%.

The developed rating curves for both hydrological years provide very satisfactory estimates of SSC from discharge measurements (according to the guidelines proposed by Quilbé (2006), with a highly statistically significant relationship (P < 0.001) and explained variance of 65.21% and 60.10% for the rating curves developed from data collected in the 2007/08 (two months) and 2008/09 (complete) hydrological years. Following bias correction, relative errors are in the region of 9.2723 and -1.3267%. Unsurprisingly, given the lack of data in generated during the 2007/08 hydrological year, the rating coefficients between the years are dissimilar. There is a greater availability of sediment at low discharges during the 2008/09 hydrological year; however, during 2007/08, the SS response to increasing discharge is abrupt and steep resulting in the generation of a *b* coefficient of 1.4039, compared to 1.0675 derived from the 2007/08 data.

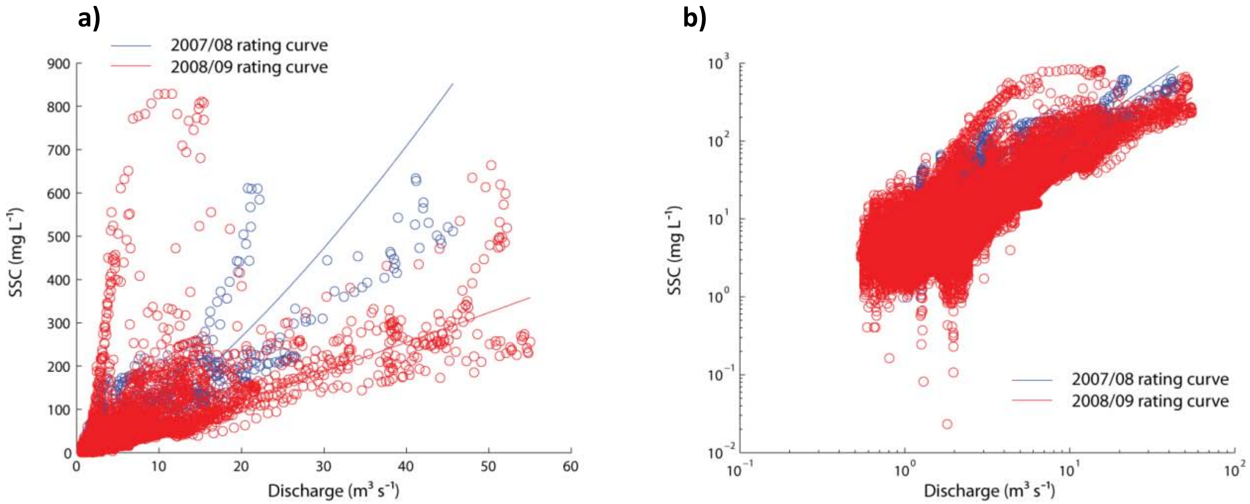


Figure 6.14: Annual sediment rating curves at Broadway Foot, river Rye

Table 6.12: Annual sediment rating curve parameters and summary of sediment loadings at Broadway Foot, river Rye.* The Duan (1983) correction factor has been applied to both years.[a] 2007/08 hydrological tear only contains two months data.

	Total Load (t)	90% transported in...	*a*	*b*	Log-normally distributed error	Coefficient of Determination (R^2)	*P*	Relative error of Estimation (%)	*β	Relative error of estimation (%) After SF
2007/08[a]	1492.5 (± 287.16)	11.29%	3.3066	1.4039	0.0828	0.6521	*<0.0001*	-16.0541	*1.3017*	9.2723
2008/09	4437.0 (± 853.68)	6.36 %	4.0200	1.0675	0.0685	0.6010	*<0.0001*	-28.2473	*1.2358*	-11.3267

Following the integration of simultaneous river flow and SSC measurements, the annual SS load was calculated. In the two months monitored in the 2007/08 hydrological year it is estimated that 1492.5 (± 287.16) t of fine sediment was transported through the river reach, equating to a sediment yield of 11.41 (± 2.20) t km^{-2}. During the complete 2008/09 hydrological year, 4437.0 (± 853.68) t of fine suspended sediment was transferred, equating to 33.92 (± 6.53) t km^{-2}. Somewhat surprisingly, this is only three times greater than the total load transported during August and September 2008. During this entire monitoring period, minimal transfer occurs under low flow conditions. This is highlighted by 90% of the total suspended sediment load being transported in 11.29% of time for the first year which falls to 6.36 % during the second year (Table 6.12).

6.5.3 Monthly and Seasonal Variability in Suspended Sediment Transfer

Within and between seasons, strong monthly fluctuations in the fine suspended sediment transfer occur. The mean monthly suspended sediment load is 423.53 t (CV = 107.61%). During the complete, second sampling year, the mean monthly load is 369.75 t (CV = 127.59%). In general, the monthly suspended sediment load ($\boldsymbol{y}$) (t) follows changes in the monthly water yield (hm3) ($\boldsymbol{x}$) reasonably well. This is highlighted in linear model ($\boldsymbol{y = 104.8x - 242.3}$; $\mathbf{R2} = \mathbf{0.53}$; $\boldsymbol{P = 0.0016}$).

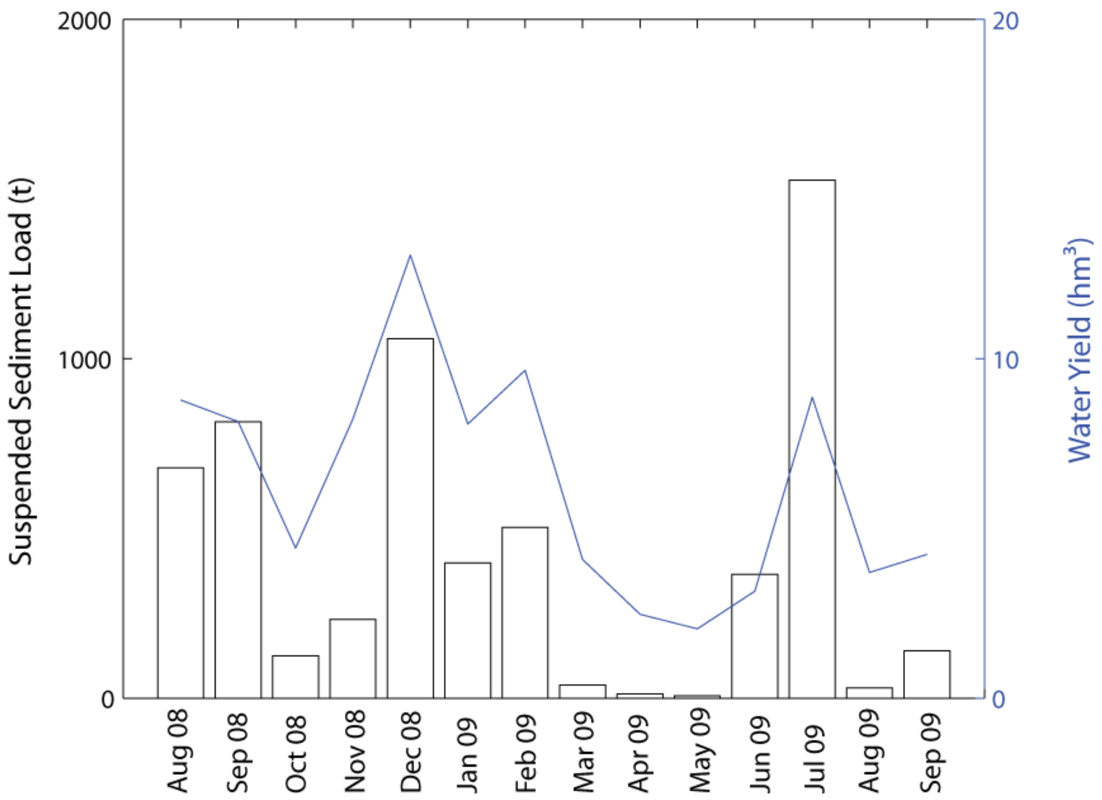


Figure 6.15: Monthly suspended sediment load (t) and water yield (hm^3) at Broadway Foot, river Rye

The seasonal SS loads are highly variable throughout the monitoring period with, for example, the SS load during spring 2009 contributing only 58.2t of sediment whereas the subsequent season resulted in the largest suspended sediment flux, with 40 times (2020.7 t) the fine sediment being transferred. This season alone accounted for over 45% of the total observed load. The seasons with the largest suspended sediment loadings (Autumn 08 and Summer 09) also contain two of the three greatest individual monthly suspended sediment loadings. These are December 08 (1060 t) and July 09 (1526 t) which are the second largest and largest respectively as shown in Figure 6.15. Within these months, large events occur which are responsible for the transfer of suspended sediment.

The relationship between monthly water yields and SS load reveals periods of the year where there is a relative depletion and also abundance of fine sediment available for transfer. These periods can be picked out visually and through the analysis of the multiple hysteresis loops of varying strengths, complexity and directions (Figure 6.16).

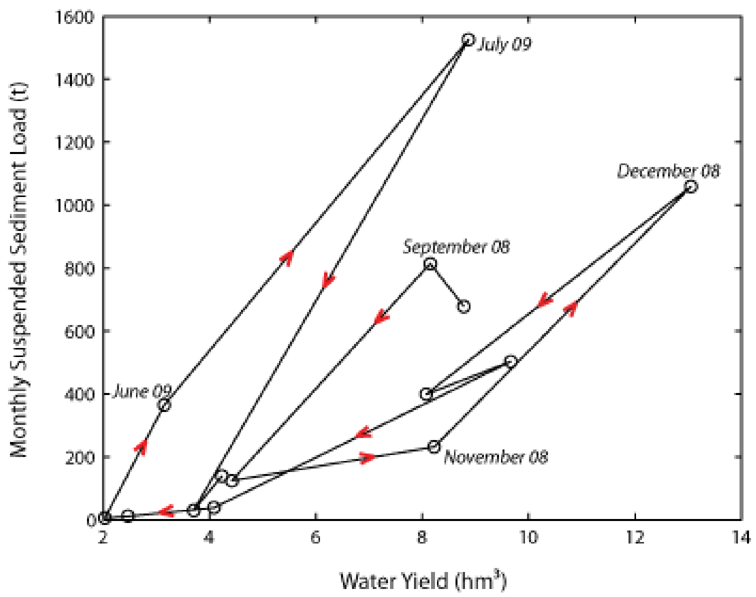


Figure 6.16: Monthly water yield and sediment load hysteresis patterns at Broadway Foot, River Rye during the 2008/09 hydrological year

This plot shows considerable variability in the total SS load for a given total monthly water yield at any one time, resulting in the generation of multiple hysteresis loops. In October 2008, at the start of the hydrological year, water yield and sediment load are both low, at 4.4 hm^3 and 124.8 t respectively. In November, the water yield increases substantially to a comparable value to that seen in September 08 (8.2 hm^3). However, the increase in suspended sediment load is not of the same magnitude, with total mass of 231.7 t being transported. This is a value which is over three times smaller than the mass flux during September 08. In November and December 08, a large increase in water yield occurs, up to a maximum total value of 13.1 hm^3. This results in an increase in suspended sediment loads to 1059 t. The gradient of the slope between the paired water yield and suspended sediment load between these two months is comparable to that observed between

September and October 08. Following this period of peak flow, the water yield total in January 09 falls to 8.1 hm^3. At this point, the total sediment load is greater than for the same water yield on the rising limb of the hysteresis loop (398.9 t).

These findings suggest that between August and January, there appears to be a depletion of available sediment sources. In the first part of the year, relative sediment flux is high in August, September and October. However, in November through to January the monthly sediment load is diminished compared to that found at the end of summer and beginning of autumn. Secondly, although there is still relative depletion in January, there is a greater availability of fine sediment compared to the levels in November, as shown by the negative hysteresis observed.

The final evidence of changes in sediment availability at the Broadway Foot monitoring station occurs between June and July 09. This is a period following four months of very low water yield ranging from 4.1 to 2.0 hm^3 and from the monthly hysteresis plot, appears to be a period where sediment is most available for transfer. In June, a small peak in total water yield of 3.2 hm^3 is met with a disproportionate increase in suspended sediment load, which rises to a total of 364.7 t. This 1.6 times increase in water yield produces a massive 52.9 times increase in suspended sediment load. Continual increases in total monthly sediment load to a peak of 1526.2 t are seen in July following the water yield rising to 8.9 hm^3. The total load then drops off to 30.4 t in August, despite the total water yield being greater than that of June 09.

It is hypothesised that during the previous months of low flow, a sediment preparation phase was occurring which included the gradual encroachment of fines from the surrounding hill-slopes thus producing a readily available, surplus of supply following the onset of effective flows. Evidence supporting this hypothesis is presented in the following paragraphs.

The first increases in flow during June occurred on the 5th and 9th days of the month. These events were of minimal magnitude (max Q of 1.75 and 1.48 $m^3 s^{-1}$) which were insufficient to mobilise available sediment sources (max SSC of 38.96 and 25.30 mg L^{-1}). The first flushing flow occurred on 15th June (Figure 6.17). The maximum discharge of this event is quite low (4.68 $m^3 s^{-1}$). However, it is sufficient to mobilise available sediment resulting in maximum SSCs of 555.52 mg L^{-1}. This event produces an extremely prominent anti-clockwise hysteresis pattern with SSCs increasing abruptly at peak discharges and maintaining relatively high levels during the falling limb of the hydrograph. A similarly strong anti-clockwise hysteresis pattern is observed during the next transfer event which occurs on 23rd June. This is of a much greater magnitude with peak Q of 15.4 $m^3 s^{-1}$, which produced a maximum SSC of 828.69 mg L^{-1}. The final transfer event of the month involves two consecutive discharge pulses which begin on 27th June. The maximum flow of the first pulse is 6.54 $m^3 s^{-1}$ followed by 12.5 $m^3 s^{-1}$. The associated maximum SSCs are 551.8 and 472.3 mg L^{-1}. Although both of these pulses result in the production of anti-clockwise hysteresis, there is the first evidence of a reduction in the sediment supply with a reduction in peak SSCs of 79.5 mg L^{-1} despite the peak flow of the second pulse being 5.96 $m^3 s^{-1}$ greater. Given that anti-clockwise events are typically associated with the mobilisation of sediment from sources distal to the main channel (Eder et al., 2010) and when readily accessible sediment sources proximal to the channel are not present (Marttila and Kløve, 2010), this provides support that a preparation phase during the previous months had enhanced the accessible sediment stock on the hillslopes, which could be readily mobilised following intense rainfall.

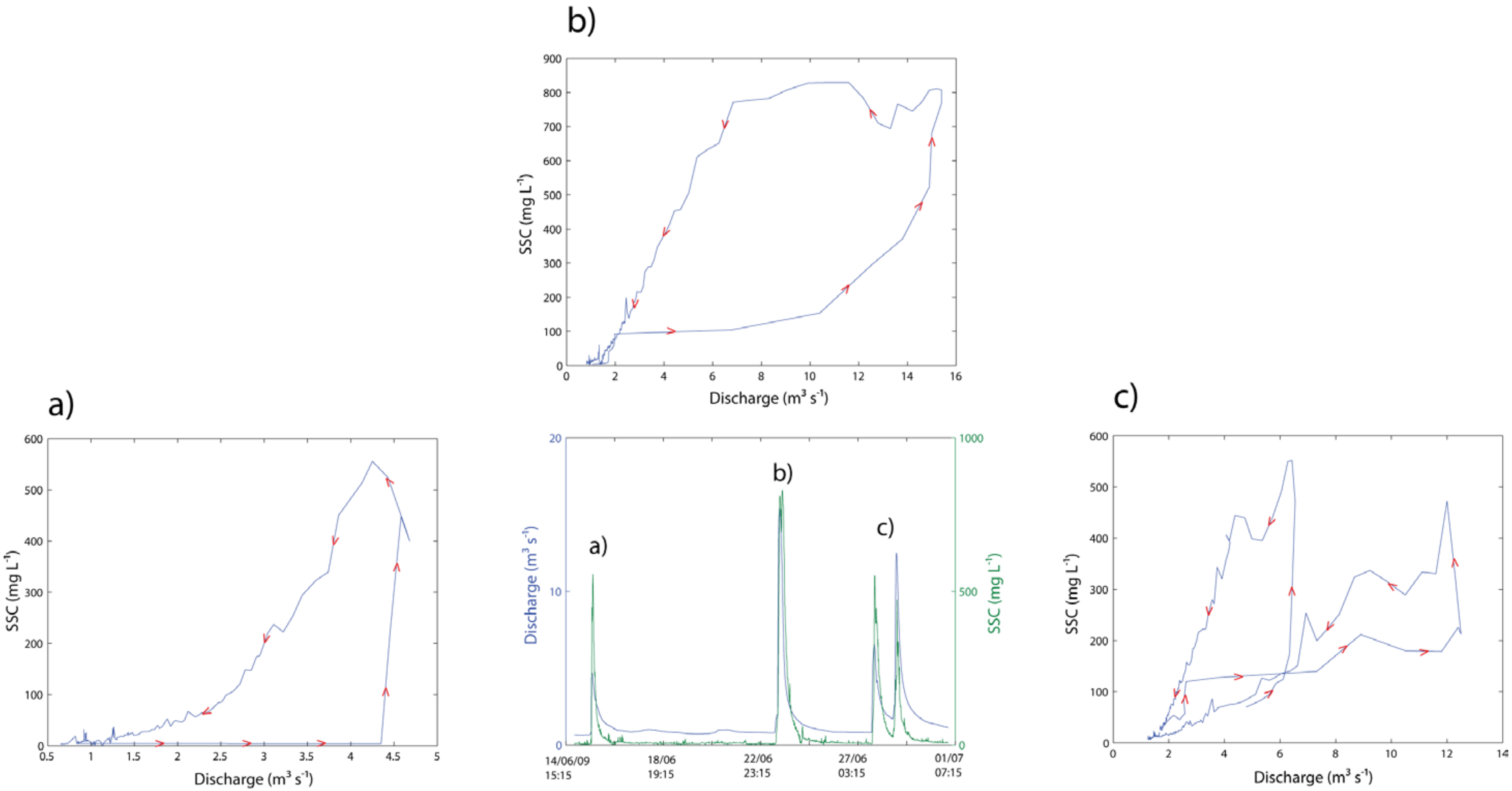


Figure 6.17 a) First **b)** Second and **c)** Third hydrological events of June 09 producing strong anti-clockwise hysteresis at Broadway Foot, river Rye

Following June 2009, suspended sediment transfer is even greater in July 2009 (yield of 1526.2 t). Accompanying these higher loads is a change in the hysteresis patterns with high magnitude clockwise hysteresis events dominating. The first increase in flow during this period occurs on 3rd July and is quickly followed by an increase on 11th July. However, neither of these discharge fluctuations produced the force necessary to transfer the available fine sediment. Resultantly, the maximum SSCs occurring were 22.69 and 25.54 mg L^{-1}. The first mobilising event was however of considerable magnitude. This event occurred on 16th July 09 with a maximum discharge of 52.2 $m^3 s^{-1}$ and maximum SSC of 663.57 mg L^{-1}, resulting in an event suspended sediment load of 1324.9 t. This individual event accounts for 86.1% of the total monthly load and is characterising as displaying strong clockwise hysteresis. The remaining events in July 09 are somewhat smaller in magnitude, with the event beginning on the 23rd July having peak discharge and SSCs of 15.8 $m^3 s^{-1}$ and 268.67 mg L^{-1} respectively. This event provides evidence of a first flush (clockwise hysteresis) between 2.50 and 5.00 $m^3 s^{-1}$ which is possibly due to the removal of deposits which had been deposited on the falling limb of the previous large event. Throughout the remainder of the event, SSCs are somewhat reduced compared to those in June 09, resulting in an event load of 70.10 t and potentially highlighting the occurrence of reductions in sediment stock. The final event of the month occurred on 29th July and produced a peak discharge and SSC of 20.00 $m^3 s^{-1}$ and 555.06 mg L^{-1}. The initial increase in discharge once more produces a rapid rise in SSCs, with high concentrations on the rising limb acting to produce strong clockwise hysteresis.

The shift in hysteresis patterns from anti-clockwise at the end of an extensive period of limited runoff to being dominated by clockwise hysteresis during high magnitude events during a wet period clearly indicates the occurrence of multiple processes of sediment generation across the catchment. It may be that during the period of limited runoff, between January and May 09, an enhanced sediment stock was developed on the hill-slopes which were accessed during the resulting moderate run-off events during June 09, acting to produce a series of anti-clockwise hysteresis. The subsequent high intensity runoff events in July, however, were able to access a distinct, large sediment stock which was subsequently transferred resulting in the production of a series of relatively high-magnitude clockwise hysteresis events.

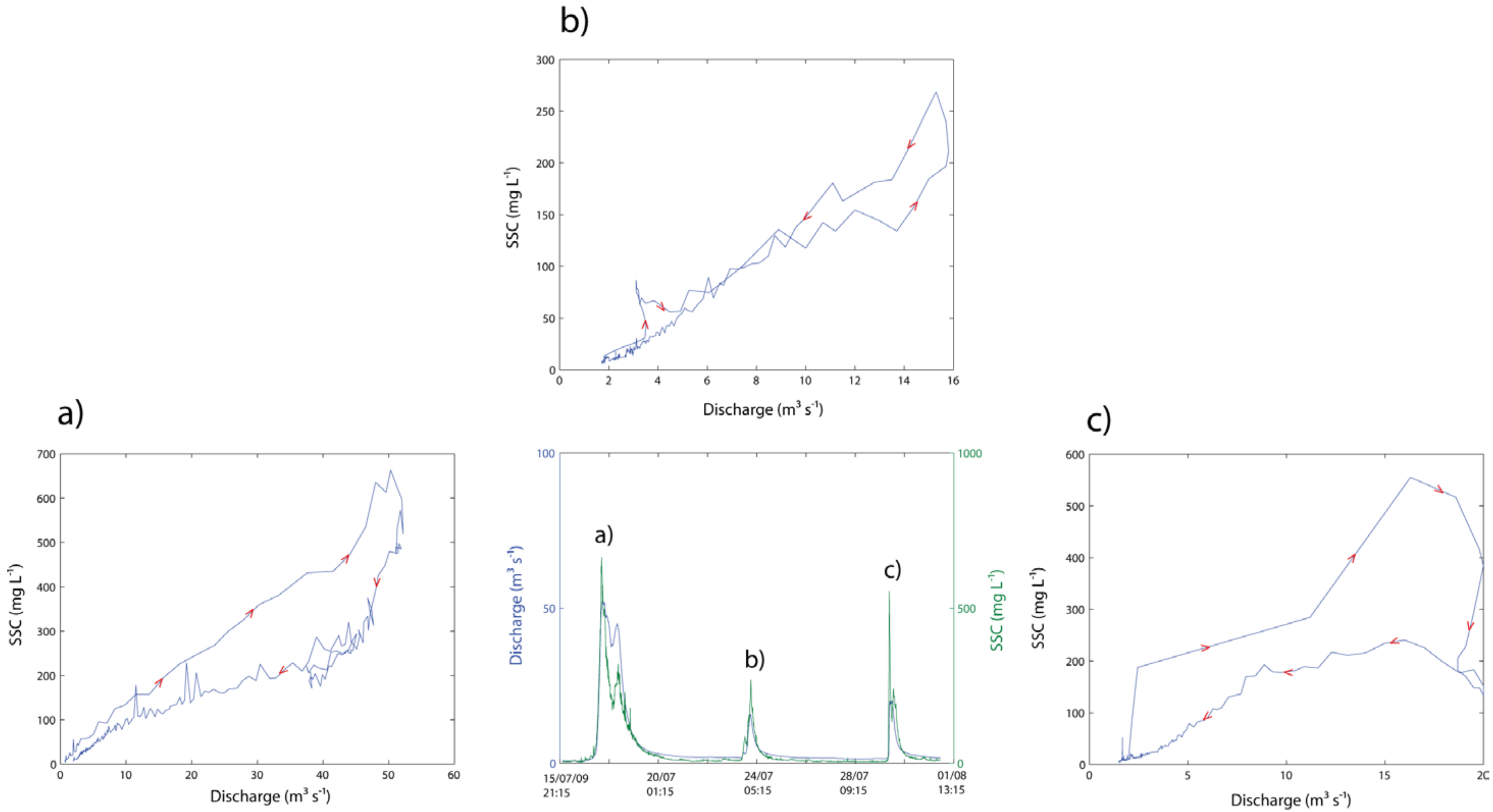


Figure 6.18 a) First **b)** Second and **c)** Third hydrological events of July 09 producing varying hysteresis patterns at Broadway Foot, river Rye

6.5.4 Within Storm Sediment Dynamics

6.5.4.1 Importance of Infrequent Events

The analysis of seasonal and monthly fine sediment flux dynamics has highlighted time periods during the year which are responsible for the transfer of fine suspended sediment in the Rye catchment above the Broadway Foot monitoring station. However, on a shorter time-scale there is often a large amount of variability in the timing of fine sediment transfer, with a substantial mass of sediment often being transported in a very short period of time. This is exemplified by 1324.9 t of sediment being transferred during four consecutive days in July 2009. This mass equates to 29.86% of the total annual load.

6.5.4.2 Assessment of Event Hysteresis Patterns

Given the importance of these short periods of high flow and sediment flux for the overwhelming majority of sediment transfer, analysis within this section is focussed on the within-storm fine suspended sediment dynamics of episodic transfer events. Separate events were defined in the hydrological series visually where a marked increase in discharge occurred. In the case of back to back events, these were analysed individually. For the River Rye above Broadway Foot during this monitoring period 61 events were successfully monitored. Patterns of hysteresis were classified based on the criteria outlined by Williams *et al.* (1989) (Table 6.13).

Hysteresis Condition	*Number*	*Median event total Load (t)*
Clockwise	9	55.65
Anti-clockwise	11	23.60
Figure of Eight (anti-clockwise loop)	3	94.95
Figure of Eight (clockwise loop)	2	457.74
Nearly none	36	4.21

Table 6.13: Summary of hysteresis patterns observed at Broadway Foot, River Rye

This shows that events displaying nearly no hysteresis dominate the total number of events, accounting for 59.02% of the total number of events and transfer a total of 2038.7 t of fine suspended sediment, which equates to only 38.35% of the total load. Although events exhibiting clockwise and anti-clockwise hysteresis only account for 16.39 % and 18.03 % of the total number of events, they transfer a disproportionate mass of sediment i.e. Clockwise events transfer 1793.0 t, with anti-clockwise events transferring 712.33 t which equates to 31.09 % and 12.35 % of the total event load respectively. This clearly shows that the magnitude of clockwise and figure of eight (clockwise loop) hysteresis events represent episodes of vast sediment transfer. In fact, the largest event transports 1324.9t of fine sediment (33% of annual load) and exhibits clockwise hysteresis, with the second largest which is responsible for the transfer of 889.24t of fine suspended sediment (20% of annual load) exhibiting figure of eight (clockwise loop) hysteresis (Figure 6.19 a & b). However, the third largest event exhibits nearly no hysteresis and is responsible for the transfer of 781.54t of fine sediment (Figure 6.19 c).

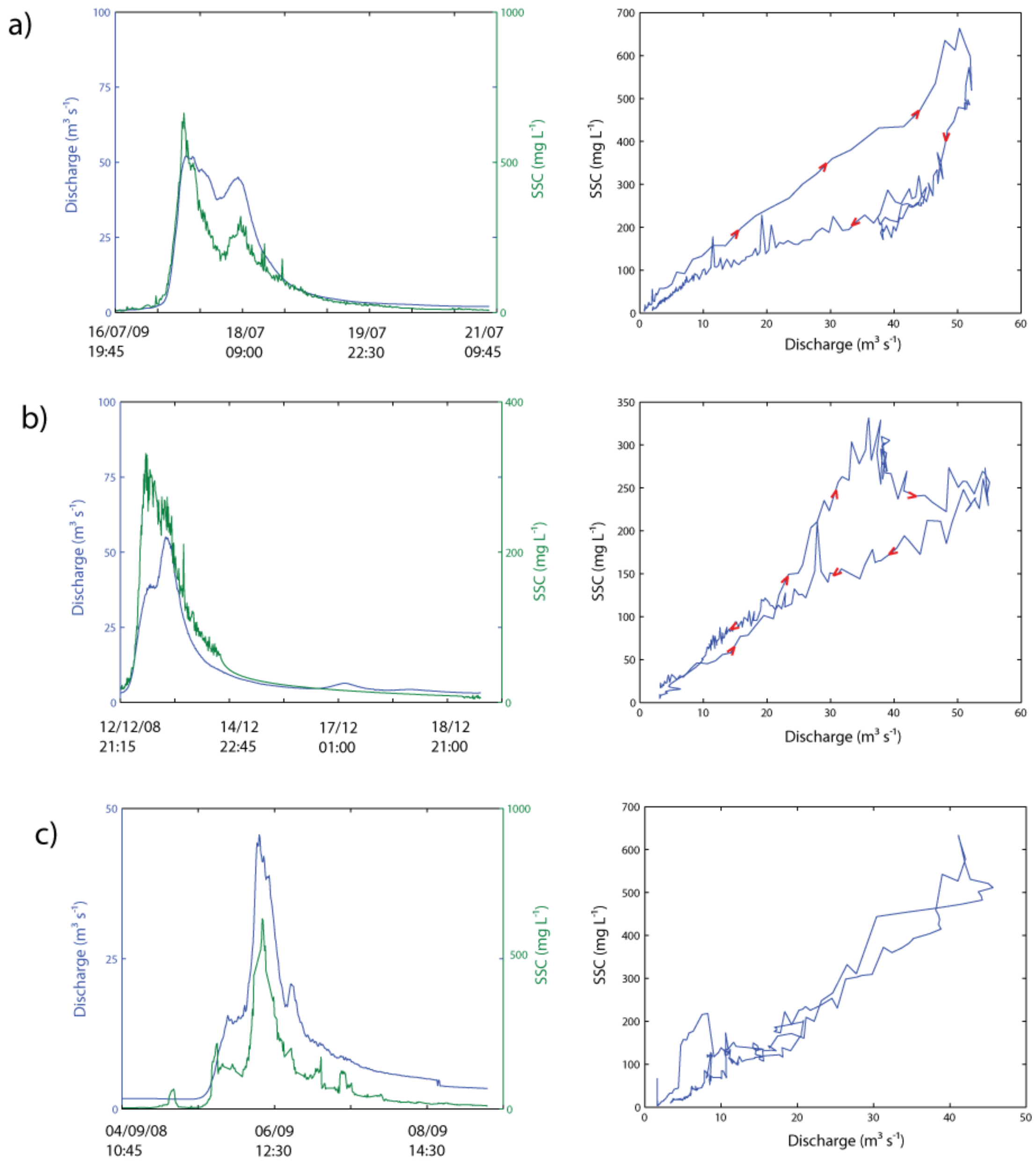


Figure 6.19 a) Large clockwise hysteresis event during July 09; **b)** Large figure of eight (clockwise loop) hysteresis event during December 08 and **c)** Large event occurring during September 08 exhibiting nearly no hysteresis at Broadway Foot, River Rye

After performing a Wilcoxon-Mann-Whitney non-parametric test, it was confirmed that statistically significant differences exist between the nearly-no hysteresis condition and clockwise ($P < 0.001$), anti-clockwise ($P = 0.008$), and Figure of Eight (anti-clockwise loop) ($P = 0.019$). No other significant differences were found between the hysteresis conditions and median event loads. This illustrates the relative variability in event SS loads for each hysteresis condition (with the exception of the nearly-no hysteresis group). This was not been observed in the Esk catchment and illustrates the highly dynamic nature of SS responses in the Upper Derwent with a range of sediment sources during both low and high magnitude events.

Nearly no hysteresis and negative hysteresis events which are seen frequently in the Upper Rye catchment are typical of rivers where there is no depletion of suspended sediment stores with accessible sediment transport pathways. Sediment sources tend to be associated with the delayed transfer of material transferred from the hill-slope and surrounding landscape. However, despite the greater frequency of these events, the relatively infrequent clockwise and figure-of-eight (clockwise loop) events do transfer a considerable mass of material, which may be associated with sediment being entrained from areas proximal to the river channel, which are readily mobile and become easily entrained at the beginning of flow events. Such sources could be exposed area of banks, or sediment which has been deposited at the foot-slopes, or even the river bed during the falling limb of previous storms, or has been temporarily stored following the failure of a river bank between high-flow events.

6.5.4.3 Quantitative Assessment of Event Hysteresis Patterns

Following calculation of the hysteresis index proposed by Lawler *et al* (2006), descriptive statistics for the events are calculated. There are a total of 26 positive and 34 negative events. It was not possible to calculate the hysteresis index for one event due to the distribution of the data. The mean and median are both negative, with values of -0.3295 and -0.0476 respectively, with a range spanning from -5.3887 to 1.0994. The standard deviation is 1.0391, signifying quite a considerable variability in the HI values.

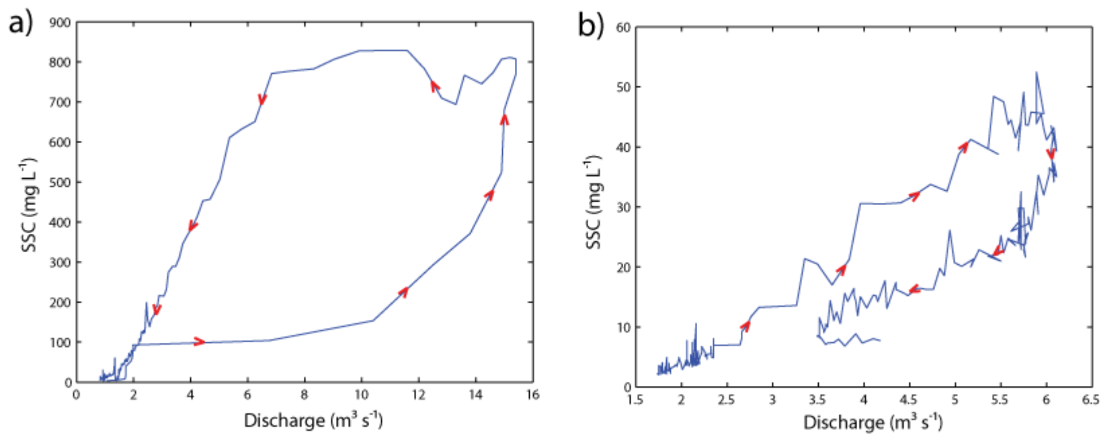


Figure 6.20 a): Negative HI event on 23rd June 2009 with a value of -5.388 and **b)** Positive HI event on 23rd November 2008 with a value of 1.0994 at Broadway Foot, River Rye

Following partitioning of the dataset into positive and negative classes, a Wilcoxon-Mann-Whitney non-parametric test was conducted to test for differences between the negative and positive groupings for median suspended sediment loads. No statistically significant differences between the groups were obtained (Z = 1.2904; *P* = 0.0985). The median load of positive events is 20.69 t (MAD = 19.57 t) and the median load for negative events is 20.43 (MAD = 17.45 t). This demonstrates that there is negligible difference between the mass of sediment transferred during positive and negative hysteresis events. Event hydrological variables are also unable to predict the HI (e.g. max Q; *P* value = 0.3305).

6.5.5 Section Summary

(1) Over the entirety of the monitoring period, the average SSC is 15.36 mg L^{-1}. In the complete 2008/09 hydrological year, the SSC ranges from 0.02 – 828.69mg L^{-1} with a mean SSC value of 13.87 mg L^{-1}.

(2) During the two months monitoring during the 2007/08 hydrological year and complete 2008/09 hydrological year, it is estimated that 1492.5 (± 287.16) t and 4437.0 (± 853.68) t of fine sediment is transported. This equates to 11.41 (± 2.20) t km^{-2} and 33.92 (± 6.53) t km^{-2} respectively.

(3) Simple rating curves are able to accurately predict SSCs from discharge measurements, providing a useful means of estimating flux at this location in the short-term where only Q data exists.

(4) Within and between seasons, strong monthly fluctuations in the fine suspended sediment transfer occur, which are largely a function of the total monthly water yield although some hysteresis is observed. For example, there is evidence of depletion between August 08 and January 09 followed by a preparation phase of low flow through to May 09. Anti-clockwise events, potentially representing hillslope sources were observed during low magnitude events throughout June 09 with higher magnitude events during July 09 exhibiting clockwise hysteresis which potentially represent sources proximal to the channel.

(5) Events displaying nearly no hysteresis dominate the total number of events (59.02 %) but only transfer (38.35 %) of the total load. Clockwise and anti-clockwise hysteresis events only account for 16.39 % and 18.03 % of the total number of events but transfer 31.09 % and 12.35 % of the total event load respectively.

(6) Statistically significant differences exist between the nearly-no hysteresis condition and clockwise ($P < 0.001$), anti-clockwise ($P = 0.008$), and Figure of Eight (anti-clockwise loop) ($P = 0.019$). No other significant differences were found.

6.6 Chapter Summary

This chapter has demonstrated how the transfer of fine suspended sediment varies over annual, seasonal and monthly timescales in addition to assessing the within-storm sediment dynamics at two sites in on the Esk River and one on the River Rye in the Upper Derwent catchment. This has provided an in depth assessment of the controls of fine sediment transfer within the catchments. A summary of the observations for each monitoring station is provided in Figure 6.21. This diagram utilises the framework of analysis (Figure 6.1) with the findings of this chapter replacing the sub-section headings.

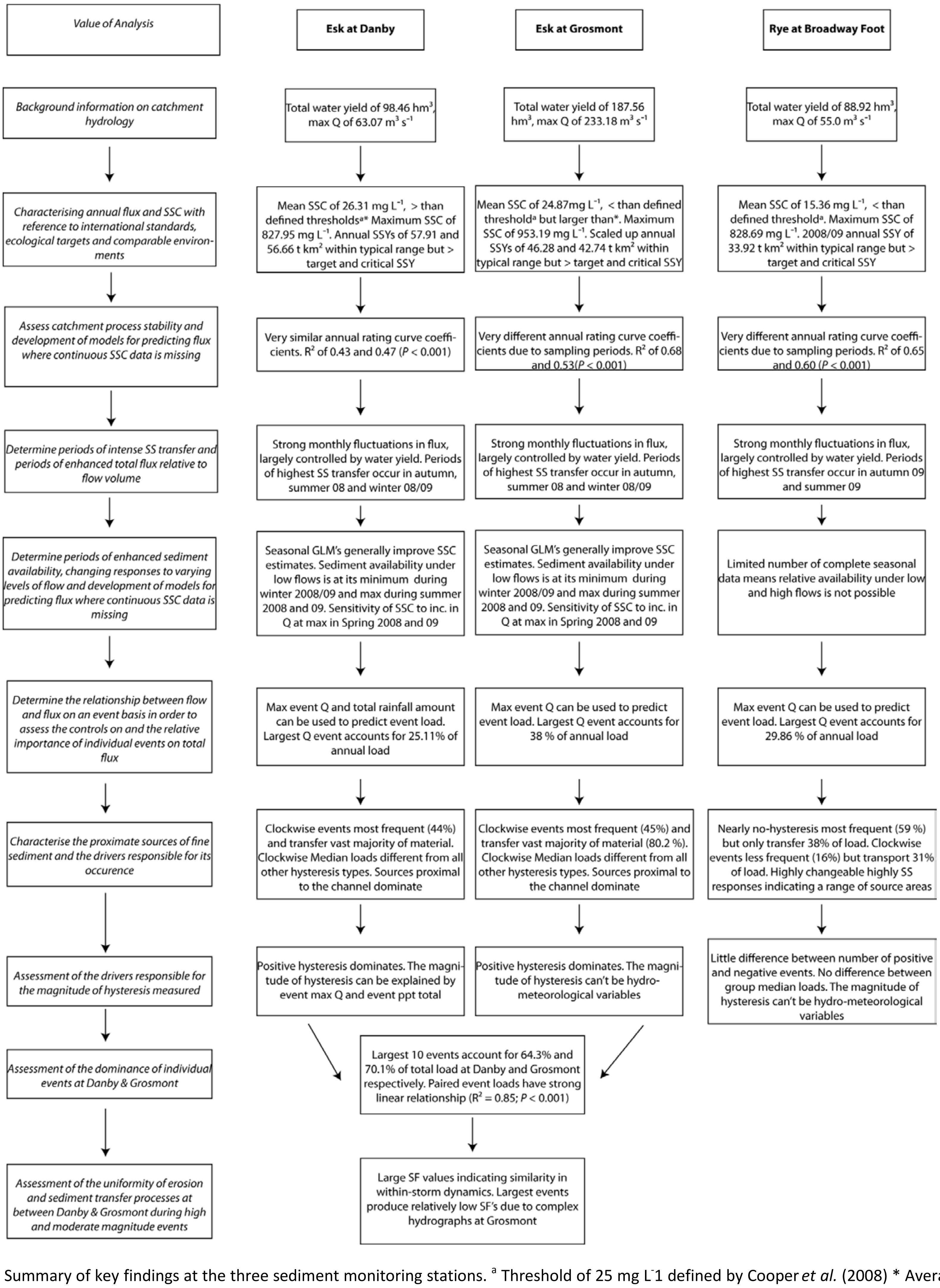


Figure 6.21: Summary of key findings at the three sediment monitoring stations. [a] Threshold of 25 mg L^{-1} defined by Cooper *et al.* (2008) * Average value of 10 mg L^{-1} defined as upper threshold for good ecological conditions for Pearl Mussels by Stutter *et al*., (2008). Target and critical thresholds noted have been developed by Cooper *et al*. (2008) .

Chapter 7: Application of Research

7.1: Introduction

This thesis has critically evaluated the spatial and temporal variability of fine sediment flux and physical properties of suspended sediment transfer in the Esk and Upper Derwent catchments, North Yorkshire using a combination of spatially extensive and locally focussed sampling techniques. This has increased both general knowledge of fine sediment dynamics in upland catchments and highlighted problem areas at the local catchment scale. Given the growing need for competent authorities to highlight areas of catchments where fine sediment flux is greatest (SedNet, 2009; Collins and Anthony, 2008a; Blum and Eswaran, 2004), a combination of the knowledge and methodologies presented here may be used to aid in the management of these important issues. The aim of this chapter is to apply these methods and general knowledge of fine sediment dynamics in addressing current management problems in the study catchments. In the examples that follow, four real-world case studies of fine sediment problems in the Esk catchment are discussed and the data collected as part of this research are used to help resolve these upland catchment management issues. The four documented case studies illustrate several key management scenarios:

(a) Evaluating the success of channel diversion in reducing fine sediment flux (Figure 7.1);

(b) Assessing the impact of riparian woodland management (logging) on suspended sediment flux (Figure7.1);

(c) Monitoring water quality to aid in the protection of protected and vulnerable species; and,

(d) Using fine sediment flux information to test the predictions of a risk-based diffuse pollution model (SCIMAP).

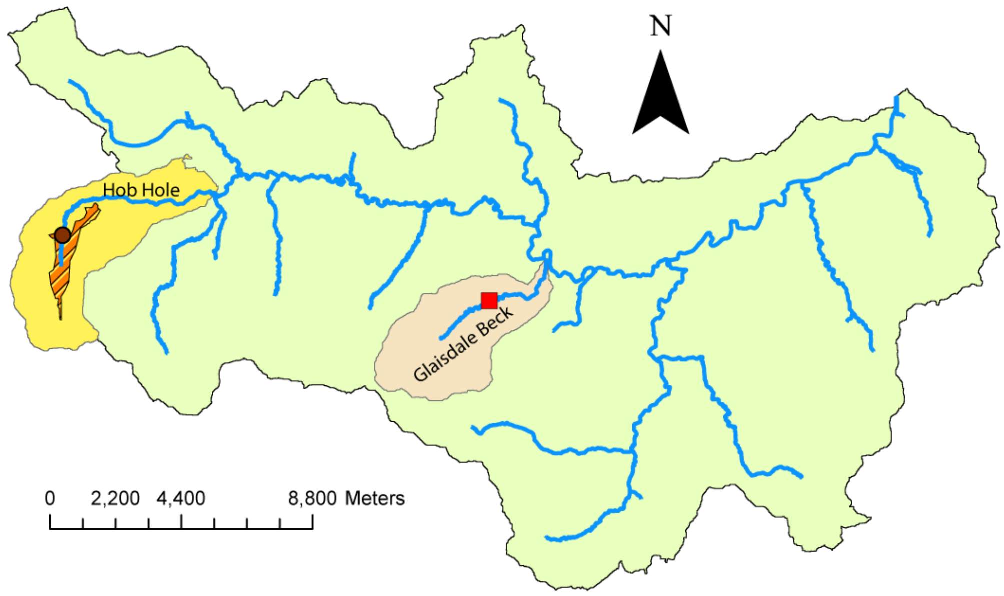


Figure 7.1: Diagram showing the location of case study **(a)** in the Glaisdale Beck sub-catchments and; **(b)** in the Hob Hole (Baysdale Beck) catchment. The red symbol represents the location of channel diversion. The orange area represents the area of riparian woodland management. Case studies (c) and (d) are catchment-scale issues.

7.2 CASE STUDY 1: Assessment of the Success of River Straightening (diversion): The Case of Glaisdale Beck

7.2.1 Context and Problem

Research in the Glaisdale Beck catchment has been driven by the necessity to: (1) determine the water quality status of the river in respect to fine sediments; (2) understand the suspended sediment processes operating in a sub-catchment that has previously been identified as a significant contributor of fine suspended sediment to the greater Esk catchment (Bracken and Warburton, 2005) and; (3) assess the effects of management practices in the catchment, specifically the realignment of the channel as a means of reducing fine sediment inputs to the river.

The Glaisdale Beck catchment is a 15.56 km^2 catchment, draining an area of the NYMNP to the south of the main Esk River. It joins the main Esk in the central valley at a distance of 32.01 km downstream of the source. Analysis of the flux data from the TIMs monitoring campaign highlighted that it has the 2nd largest SSY of all of the tributaries in the catchment and is an area responsible for elevated fine sediment transfer.

Following consultation, a reach of ~ 100m in length was highlighted as being a potentially important source of fine sediment to the beck (Warburton, 2007). This was highlighted as a within-channel source area which is characterised by near-vertical, high (~3m) banks made up of unconsolidated sediments (Figure 7.2) overlain by shallow surface vegetation. This area is grazed by livestock (mainly sheep and cattle) which had access directly to the beck. The transfer of material to the beck was also exacerbated by the progressive movement of a large hill-slope failure complex (Figure 7.3). Therefore a solution to this problem was to divert the existing channel away from the base of the eroding slope and re-establish the stream course further to the north.

Figure 7.2: The extent of bank erosion along Glaisdale Beck. Source: Jeff Warburton.

Figure 7.3: The landslide complex zone adjacent to Glaisdale Beck. Source: Jeff Warburton

In the medium and long term, the disconnection of an immediate sediment source from the watercourse may have demonstrable impacts on the suspended sediment load, in-stream ecology and habitat quality. However, projects such as these which involve the re-direction of flow inevitably involve the disturbance of the local substrate as the new channel becomes established. As a result of these modifications, a temporary disequilibrium may be created resulting in the active adjustment of the channel to the new conditions. During this period it is important that the extent of this disturbance and its potential effects be monitored.

Previous work has demonstrated the potential impact of such disturbances; suspended sediment loads immediately downstream of in-stream works have been shown to be 40% greater than those immediately upstream (Brookes, 1987) or even as much as 150% (Sear and Archer, 1998). This may itself have impacts on the river's ecological function, with fines becoming mobilised. Furthermore, by straightening the river course, the flow-path length is reduced which acts to increase the local slope. By altering the channel hydraulics, greater potential energy is available for sediment transfer which is likely to disrupt the established dynamic equilibrium. In response, the river will progressively erode the river bed in a headwards direction, reducing the level of the bed, remobilising sediments and reorganising bed-form configurations. As the level of the river bed falls, the banks may become destabilised due to undercutting. These processes will continue until either the channel becomes wide enough to dissipate the energy, or the slope of the river is reduced to a level whereby the sheer stress imposed is in equilibrium with the cohesive strength of the river bed and banks. It is of upmost importance therefore that following the increase in the reach average slope, the local slope is controlled e.g. using artificially engineered drop structures.

Due to these challenges and the sensitive nature of upland areas, this kind of channel management strategy is rarely attempted in the UK e.g. the River Habitat Survey conducted by the Environment Agency (Environment Agency., 1998) which found that 0% of upland rivers of the UK had been straightened. In contrast, straightening had been carried out on 6.2% of lowland rivers (Environment Agency., 1998) with up to 96% of lowland river channels in south-east England being modified in some way (Brookes, 1995b). Although the spatial coverage of River Habitat Survey in the UK is not complete, the systematic approach does highlight that very few reaches in the uplands of the UK have undergone this type of modification. The straightening of Glaisdale Beck as a mitigation measure is therefore one of the few projects of its kind in the UK uplands.

7.2.2 Management Action

The work that was undertaken to straighten Glaisdale beck is shown in Figure 7.4 and detailed in Table 7.1. After a prolonged period of consultation between the NYMNP, EA, land-owners and local fisheries groups, a decision was made in 2007 to divert the flow away from this highly unstable section. Channel diversion of the stream was achieved by excavating a new channel across the neck of a pre-existing bend and was completed on 10th October 2007. This shortened the length of the river by approximately 250 m.

Date	Action	Effect
October 2007	Initial diversions of Glaisdale Beck, reducing the original reach length from 375m to 125m.	Reduce sediment inputs from an area of extensive bank erosion Local slope increased to ~0.05 m m^{-1}
	Drop structure installation along new section	Prevent headward erosion
	Boulder revetment along the outside of the new meander	Prevent the beck reverting to its previous configuration. Reduce the potential for bank erosion
Spring 2008	Seed the bare banks	Promote development of grass species to provide functional strength of the banks
February 2008	Bed check weir (at location marked A in Figure7.4) Re-grading of the banks of the new stream bend and repositioning of large boulder revetments	Prevent further headward erosion Reduce vulnerability of banks to undercutting and slumping during high flows

Table 7.1: Outline of the management work undertaken in the Glaisdale Beck sub-catchment

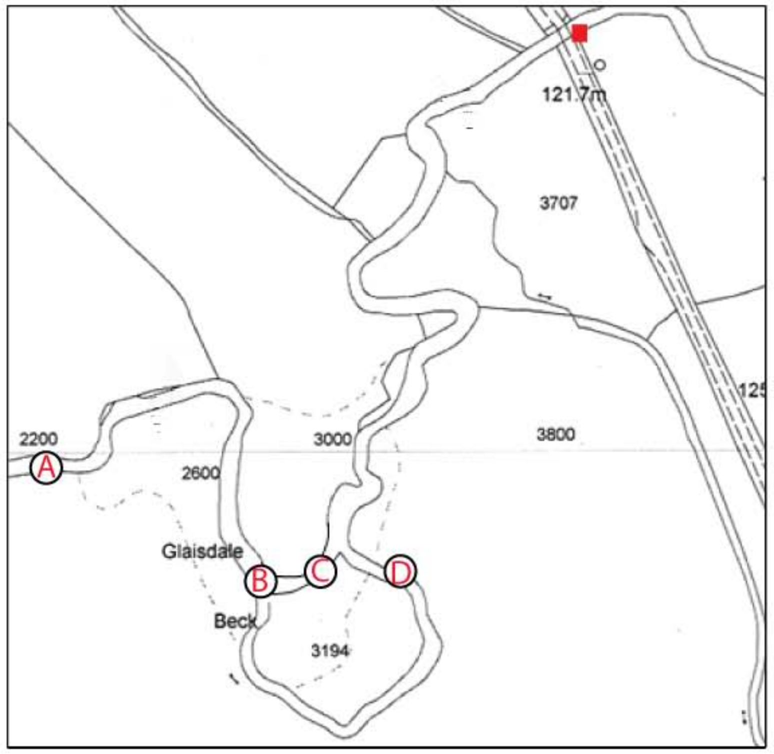


Image A: Shows a check weir which was built in February 2008 as a means of creating a step thus acting as a means of containing erosion of the river bed upstream of this point. This was in response to the mixed success of the lower check weirs shown in images B and C.

Image B: Shows the design of the new stretch of river. A new bank has been created at the apex of the meander, where the river would previously have continued straight on. The banks have been re-graded and seeded to enhance stability and large boulders have been placed on the outside of the bend to further protect the bank.

Image D: Taken following the diversion shows the remnants of the now abandoned channel. Some water is still present in pools and the channel is now vegetated.

Image C: Shows the design of two check weirs along the new river section. These were installed to prevent headward erosion of the river bed which would remobilised bed material and undermine existing banks.

Figure 7.4: A plan view of the organisation of Glaisdale Beck and the re-profiled section. Letters indicate the photos. The red square represents the location of the turbidity monitoring station

7.2.3 Application of current research: Results from Glaisdale Beck Fine Sediment Monitoring

The first year of monitoring flow and suspended sediment flux in Glaisdale Beck began on 1st October 2007 and continued through to 30th September 2008. Monitoring was extended in the following year and ceased on 30th September 2009. River level and turbidity were continuously monitored downstream of the diversion and recorded a total of 116 flow events. Mass flux was also monitored both upstream and downstream of the diversion.

Over the course of the monitoring period the total water yield was 10.83 hm^3 with discharge ranging from 0.07 to 7.06 $m^3 s^{-1}$. The mean value was 0.17 $m^3 s^{-1}$ with a standard error of 107.11%. In the 07/08 and 08/09 hydrological years the annual water yield varies from 4.99hm^3 to 5.84hm^3 with a range in discharge of 0.07 to 7.06 $m^3 s^{-1}$ and 0.10 to 4.13 $m^3 s^{-1}$ respectively. The mean Q was 0.16 $m^3 s^{-1}$ and 0.18 $m^3 s^{-1}$ respectively with associated standard errors of 115.50 and 99.32%.

Given that the data presented accounts for only 10 days monitoring prior to the modification of the channel, the suspended sediment monitoring data characterises the river regime immediately following the re-routing of the channel and shows the response of the channel during the first and second year post-modification. The comparison of annual sediment load and water yields for 2007/08 and 2008/09 make it possible to compare how the sediment transport regime has responded to the initial change in channel characteristics.

The total annual suspended sediment loads for 07/08 and 08/09 are 425.1 and 368.0 t respectively. This equates to suspended sediment yields of 35.1 and 30.4 t $km^{-2} yr^{-1}$. The mean suspended sediment concentration for the entire monitoring period was 34.38 mg L^{-1}

(SE = 159.50%). During the first and second year this value was 36.07 and 32.69 mg L^{-1} respectively. The standard error of 161.84% obtained during the first year is greater than the 156.90% derived from the subsequent year's monitoring. The mean suspended sediment concentration values are high indicating a relative abundance of fine sediment stores within the catchment which are easily accessible under low and moderate flow conditions. To put this into context, the EU FFD recommends that SSC should not exceed 25mg L^{-1} except under exceptional circumstances (e.g. storms) as it may be harmful to Salmonid and Cyprinid fish populations (Bilotta et al., 2010; Collins and Anthony, 2008a). The relatively high base flow component in the SSL contributions is further illustrated by the fact that 90% of the total fine suspended sediment load is transported in 31.8 and 43.7% of time for 07/08 and 08/09 respectively (see Table 7.2).

	Total Load (t)	50% transported in...	90% transported in...
Glaisdale Beck 07/08	425.1	1.1%	31.8%
Glaisdale Beck 08/09	368.0	1.8%	43.7%

Table 7.2: Summary of annual sediment loadings at Glaisdale Beck

Between the first and second years of monitoring, there is a 13.4% reduction in suspended sediment loads and mean SSC. It would follow that a coupled reduction in annual flow would also be observed. However, mean discharge actually increased from 0.16 m s^{-1} in 07/08 to 0.18 m s^{-1} in 08/09. Simultaneously, a smaller proportion of sediment was transported under high flow conditions (Table 7.2). Further, understanding of these apparent changes in sediment transfer patterns can be furthered through the comparison of annual sediment rating curves. These respond to patterns of sediment production, availability and transport capacity throughout the catchment (Warrick and Rubin, 2007), which in this small catchment is largely driven by the modification of the flow regime.

	Sediment Load (t)	*a*	*b*	Log-normally distributed error	Coefficient of Determination (R^2)	*P*	Relative error of Estimation (%)	B*	Relative error of estimation (%) After SF
2007/08	425.1	271.97	1.2360	1.1356	***0.52***	< 0.001	-14.95	1.1903	1.24
2008/09	368.0	193.20	1.1661	0.0468	***0.40***	< 0.001	-15.63	1.1504	-2.94

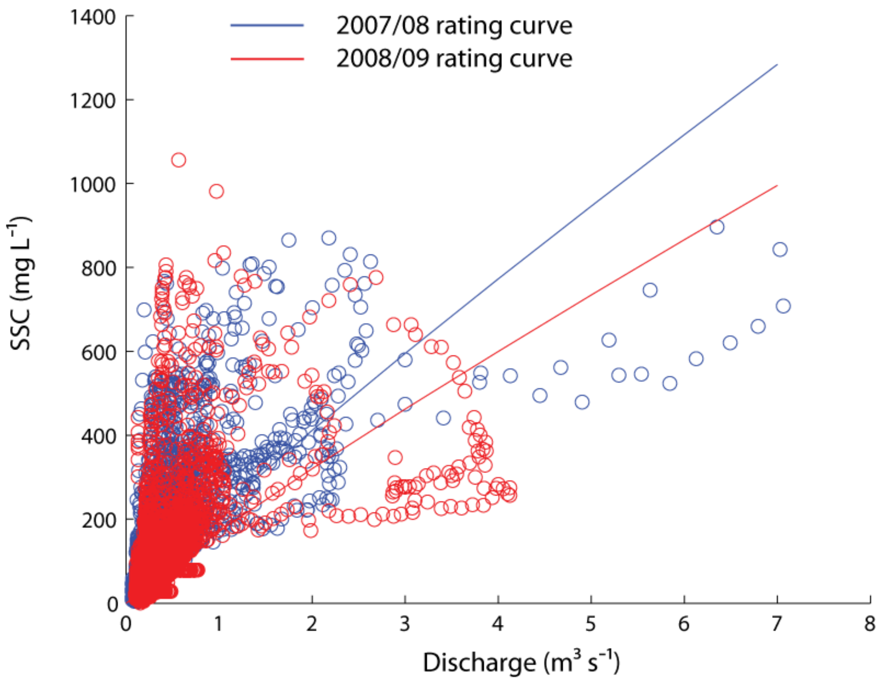


Table 7.3: Descriptive statistics and coefficients of rating curves developed for Glaisdale Beck during 2007/08 and 2008/09.* The Duan (1983) smearing coefficient yielded the smallest relative error estimation (2003) and was therefore adopted as the correction factor in this instance.

Figure 7.5: Developed rating curves for Glaisdale Beck during 2007/08 and 2008/09

The decrease in the total annual fine sediment load, whilst the mean discharge increases, combined with the observed decrease in the rating curve's *a* coefficient between 2007/08 and 2008/09 indicates a reduced availability of weathered materials that are be easily eroded and transported without significant increases in flow conditions. This highlights a potential reduction in sediment stock proximal to the channel. Interestingly, the decrease in the *b* coefficient between 2007/08 and 2008/09 is also indicative of a second change in the sediment delivery system. Suspended sediment concentrations become less responsive to increases in discharge and the erosive power of the river. It therefore seems reasonable to suggest that overall, during the first two years since diversion; the sediment delivery of system has become more restrictive, with the volume of fine sediment stock being reduced, whilst the erosive response under high flow conditions is dampened. This indicates differences in "flow effectiveness" (Hicks et al., 2000; Wolman and Miller, 1960) between the years, with the greater flows during the second year failing to have the same erosive impact as the previous year due to the sources and pathways that were activated during moderate and high flows of 07/08 being less responsive during 08/09.

Following this annual analysis of changes to the transport regime, seasonal specific rating curves are also developed as a means of determining the extent to which sediment processes vary seasonally immediately following channel modifications. Firstly, it is clear that the spring period is responsible for the lowest sediment load, with contributions of 48.2 and 29.6 tonnes for the first and second years respectively, only contributing 9.8% of the total sediment load. In contrast, the fine suspended sediment transfer between the autumn and winter and summer months is relatively evenly distributed, accounting for 27.2%, 36.2% and 26.8% of the total load respectively (Table 7.4).

From the development of season specific rating curves (Table 7.4), it is apparent that each of the models are effective in predicting suspended sediment concentrations from discharge measurements. This is indicated by the R^2 values which are all statistically significant ($P < 0.001$), and five of the eight models also meet the requirements outlined by Quilbe *et al.* (2006). Despite the overall success of these rating curves, the parameters for each of the models vary considerably. The *a* coefficient varies from between 192 to 1363.4 whilst the *b* coefficient varies between 0.99 and 2.09.

	Sediment Load (t)	Log transformed model	Log-normally distributed error	Coefficient of Determination (R^2)	Correction factor*
Autumn 07	44.85	$C = 554.00Q^{1.6227}$	0.0444	***0.63***	*1.1666*
Winter 07/08	176.9	$C = 288.41Q^{1.3843}$	0.0281	***0.76***	*1.0932*
Spring 08	48.2	$C = 433.89Q^{1.4657}$	0.0534	***0.50***	*1.1894*
Summer 08	154.8	$C = 246.71Q^{0.9902}$	0.0539	***0.44***	*1.1575*
Autumn 08	170.7	$C = 192.00Q^{1.2095}$	0.0603	***0.47***	**1.0312**
Winter 08/09	110.1	$C = 272.60Q^{1.5107}$	0.0347	***0.62***	1.0968
Spring 09	29.6	$C = 1363.4Q^{2.0850}$	0.0290	***0.40***	1.1009
Summer 09	57.8	$C = 867.93Q^{1.7930}$	0.0309	***0.61***	1.0866

Table 7.4: Model parameters and statistics for seasonal rating curves at Glaisdale Beck. *The Duan (1983) correction factor has been applied when the CF. is italicised whereas the Kao (2005) factor has been applied where the CF. is in bold.

Research has commonly found a negative relationship between the *a* and *b* coefficients of sediment rating curves developed for individual catchments (e.g. Asselman, 2000; Fenn et al., 1985; Rannie, 1987; Thomas, 1988; Walling, 1977). In catchments that are dominated by the presence of an easily accessible and erodible sediment stock, increases in discharge often have little influence in the SSCs, producing relatively flat rating curves. Alternatively, in catchments that consist of resistant materials and are highly dependent on stream power, steeper rating curves are produced. However, a lack of a statistically significant relationship between the parameters has also been documented (e.g. Mano et al., 2009; Sadeghi et al., 2008) and this has usually been attributed to variability in the sediment delivery processes under different flow conditions.

In the case of Glaisdale Beck, a positive relation between the two coefficients has been generated at both annual and seasonal time scales. One other example is from the arid Wahrane river basin (Algeria) (Benkhaled and Remini 2003). However, no plausible explanation was given for this relationship. At Glaisdale this may be a result of instability in the river reach i.e. fine sediment is readily mobilised under low flow conditions (as highlighted by the importance of high average SSCs). SSCs under high flow conditions continue to increase rapidly due to the availability of unconsolidated material on the bed and banks, leading to a positive relationship between the two coefficients. This behaviour is confirmed by the lack of substantial progressive exhaustion one would typically expect during back-to-back flow events (Figure 7.6).

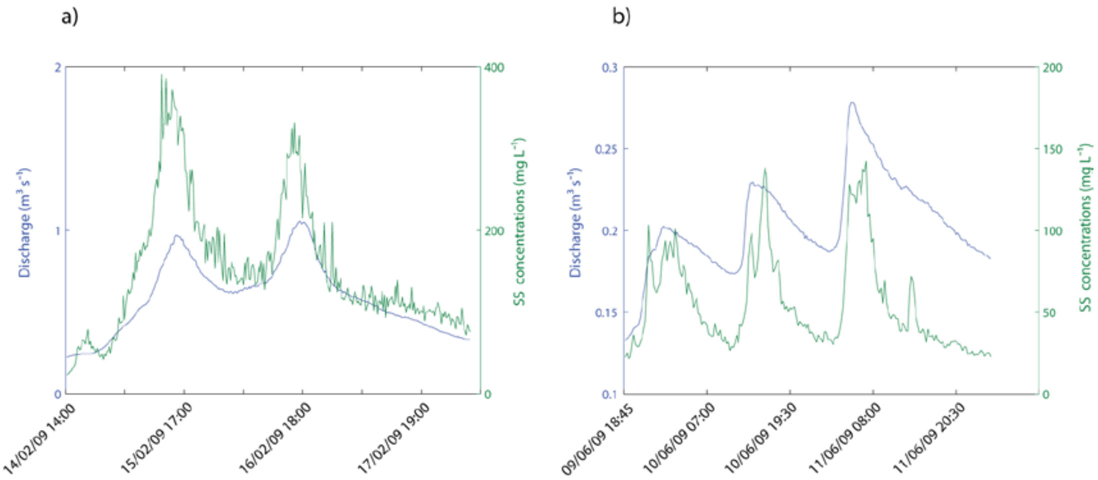


Figure 7.6: Within-storm fine sediment dynamics of back-to-back events in Glaisdale Beck in the Esk catchment during the period of **a)** 14th – 17th February 2009 and; **b)** 9th – 11th June 2009.

Although general patterns of fine sediment transfer have been established, the majority of suspended sediment is usually transported over short periods. Indeed, it is apparent that the time taken to transport 90% of the monthly suspended sediment load is negatively correlated with the magnitude of suspended sediment load ($R^2 = 0.45$; $P < 0.001$) and total water yield ($R^2 = 0.43$; $P < 0.001$). For example, in months where the fine suspended sediment load and water yield are greatest the time taken to transfer 90% of the total monthly load is very short e.g. 90% transferred in just five days in December 2008.

Given the importance of short time periods of high flow on sediment flux, this section analyses the within-storm fine suspended sediment dynamics on an event basis. During the period of monitoring, 110 events were classified and analysed for hysteresis characteristics. The classification of hysteresis patterns follows Williams (1989). The number of each hysteresis condition and associated magnitude of sediment delivery is shown in Table 7.5.

Hysteresis Condition	*Number*	*Mean event total Load (t)*	*Coefficient of Variation (CV) (%)*
Clockwise	56	9.74	184.32
Anti-clockwise	5	1.28	81.14
Figure of Eight (anti-clockwise loop)	16	2.60	71.37
Figure of Eight (clockwise loop)	---	---	---
Nearly none	29	0.99	83.98
Complex (multi peaked)	4	11.25	109.65

Table 7.5: Summary of hysteresis patterns observed at Glaisdale Beck, tributary of the river Esk

Clockwise hysteresis dominates, accounting for 52.83% of the total number of events. In total, these events transfer 545.31 t of fine sediment which equates to 81% of the total event load. When the Mann-Whitney *U*-test is conducted to ascertain differences, it was found that the sediment load generated by this group is significantly different ($P < 0.05$) from anti-clockwise ($P = 0.018$) and nearly no ($P < 0.001$) hysteresis events.

Anti-clockwise events occur infrequently whereas events exhibiting nearly no hysteresis occurs quite regularly (26.36% of the total number of events). However, both typically produce very low event suspended sediment loads, accounting for 0.95% and 4.27% of the total event load respectively.

Complex, multi-phase events only account for 3.64% of the total number of events however, they account for 6.69% of the total event load and produce event loads statistically similar to all other groups with the exception of nearly no hysteresis. Figure of eight (anti-clockwise loop) events are characterised as having an initial flush of SS transfer before subsiding and increasing once more at the time of peak flow. These events are relatively frequent in the catchment, account for 14.55% of the total number and 6.19% of the total load.

In addition to the classification of hysteresis patterns, the quantification of the magnitude of hysteresis was obtained using the dimensionless hysteresis index developed by Lawler (2006). The arithmetic mean and median of the index are both positive, at 0.55 and 0.40 respectively with minimum and maximum values of -1.55 and 3.16 respectively. The standard deviation of the data is 1.19. Of the 110 analysed events, 24 are negative with the remaining 86 being positive. Of note is the variation in the event suspended sediment load associated with the positive and negative hysteresis events. It has been found that positive events account for 602.70 tonnes of material, whereas the negative events account for a mere 64.37 tonnes. The sum of the positive events total nearly ten times that of the negative events, despite only being over four times the number of positive to negative events. Clearly the vast majority of sediment is being transported during clockwise hysteresis events.

This type of event has previously been associated with sediment delivery from within the channel itself, or from areas proximal to the river channel, where readily mobile fine sediment can be easily entrained at the beginning of flow events (Lefrançois et al., 2007; Marttila and Kløve, 2010; Seeger et al., 2004; Smith and Dragovich, 2009). Such sources could be exposed area of banks, or sediment which has been deposited at the foot-slopes, or even the river bed during the falling limb of previous storms, or has been temporarily stored following the failure of a river bank between high flow events. Such conditions are prevalent in the Glaisdale Beck diversion reach.

As an additional means of assessing the effects of management, suspended sediment flux was monitored upstream and downstream of the modified reach. Impact assessment of channel modification by monitoring upstream and downstream of the area of intervention are a favoured means of determining local changes in the sediment transfer system. They are well adopted in the quantification of the impacts of forestry harvesting (Harris et al., 2007), culvert removals (Foltz et al., 2008), dam removal (Granata et al., 2008), etc. Usually, these studies involve the application of turbidity probes and/or automatic water sampling equipment which is able to provide reliable estimates of sediment flux at quasi-continuous/discrete time intervals.

For this study, TIMs were adopted to assess the impacts of channel modification. These have been shown as an appropriate method for determining the relative suspended sediment flux of upland rivers (Appendix A) and have the benefit of allowing the assessment of sediment processes upstream and downstream of the channel modification simultaneously.

For the purposes of assessing the relative changes in sediment flux upstream and downstream of the channel modification, it was deemed sufficient to use the bank-full cross-sectional area as the scaling exponent as any changes in the cross section of flow would occur at both monitoring locations. Following the calculation of the upstream and downstream relative fluxes, the ratio between the two was computed (Figure 7.7). The use of this ratio approach allows us to identify significant shifts in erosion and deposition through the modified reach. A value less than 1.0 indicates erosion within the reach; a value greater than one indicates a reduction in load downstream and net deposition.

The mean ratio between upstream and downstream flux over the entire monitoring period is 1.06 (SE = 76.85%). However, during the 2007/08 hydrological year, this mean value is only 0.72 (SE = 56.03%), with a range of 0.31 to 1.30, although during this period there is an extended period of approximately six months with no data present due to the removal of the samplers by high flows. This period represents the middle of the year, between December 07 and June 08. The ratio of 0.72 demonstrates that, immediately following channel diversion; the modified area was undergoing net erosion with a greater mass of sediment being transferred relative to the upstream contributing area. It is believed this is a consequence of the river adjusting towards a new equilibrium.

The second year of monitoring is much more complete, with only one data point missing (between 6th March and 4th April 09). For this second year, the mean ratio is 1.27 (SE = 74.64 %). The shift in ratio highlights that the flux of sediment upstream of the diversion is greater, relative to the downstream flux. During this period, headward erosion of the river bed occurred; with the upstream drop-structure becoming undermined thereby allowing the notch to move headwards, producing further erosion upstream of the TIMs location. It appears this eroded sediment is then redistributed towards the lower end of the reach where storage of the sediments occurs upstream of the lower TIMs.

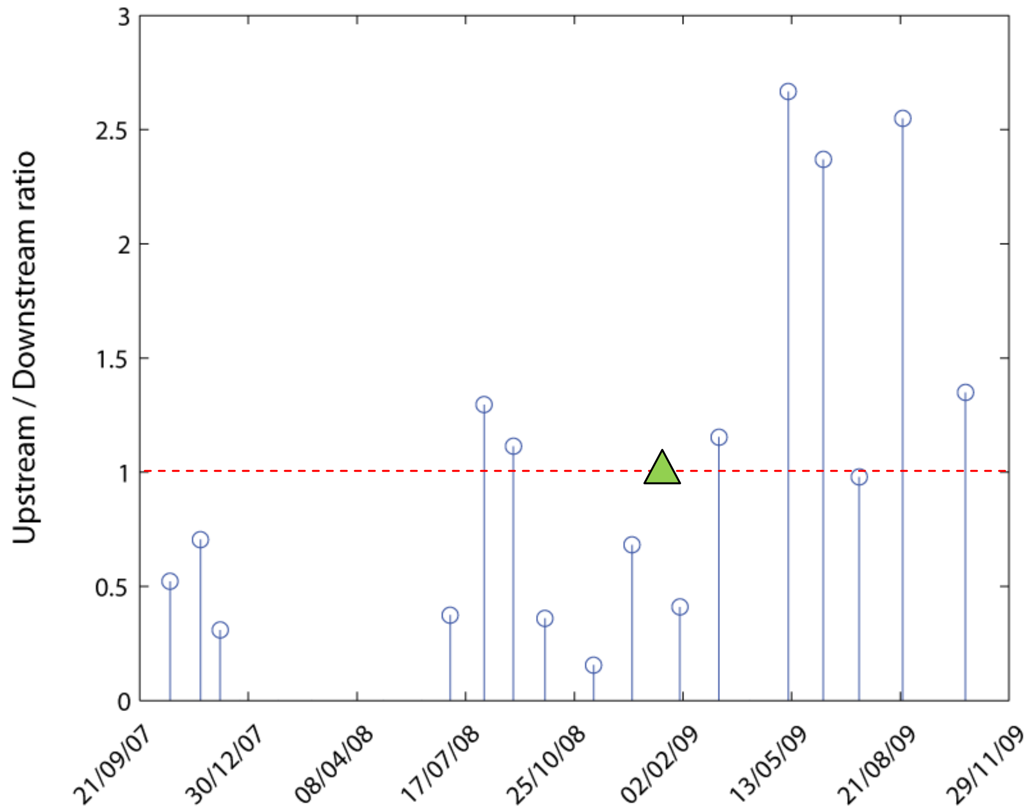


Figure 7.7: Stem plot illustrating variations in the ratio of sediment flux above and below the channel modification in Glaisdale Beck, Esk catchment. Filled triangle highlights the approximate time when headward erosion notch bypasses upstream sampler.

This case study demonstrates the power of utilising high frequency turbidity probes, coupled with low cost sampling to bracket an engineering structure can be used to understand the contemporary processes involved following the diversion of an upland river channel aimed at reducing sediment flux through the reach. Such approaches can also be used to review the success of mitigation (through long-term monitoring) relative to prior conditions and with respect to "good ecological conditions". Over the first and second years following truncation, Glaisdale Beck is currently continuing to adjust to a new dynamic equilibrium with continued channel instability; however, the sediment delivery system has become more restrictive, with the volume of fine sediment stock being reduced, whilst the erosive response under high flow conditions has also been reduced.

7.3 CASE STUDY 2: Assessment of logging activity on Sediment Flux – Baysdale Beck, Upper Esk

7.3.1 Context and Problem

In the upper headwaters of the Esk there is only one significant area of dense woodland and this is subjected to management practices (Figure 7.8). It has long been understood that forestry operation and logging activity can have negative impacts on the soil structure, enhancing the erodibility of the soil surface (Burt et al., 1983; Gimingham, 2002; McHugh, 2000; Robinson and Blyth, 1982b). This is especially true when logging activity is undertaken during waterlogged conditions. During August 2008, this situation occurred in the Kildale area of the Baysdale Beck sub-catchment of the Esk (Figure 7.8). The first instance of any issue emerged on the 14th August 2008 when members of the public reported "coloured water" along the Esk River to Environment Agency officials. An investigation subsequently took place which led to the source of the pollution being identified on the 29th August 2008.

At the time when this pollution event is believed to have taken place, the catchment was fully instrumented with suspended sediment monitoring equipment in operation at Danby and Grosmont on the main Esk River in addition to a distributed network of TIMs monitoring relative flux across the catchment. This section demonstrates the benefits of having such monitoring in place when incidents such as this pollution event occur.

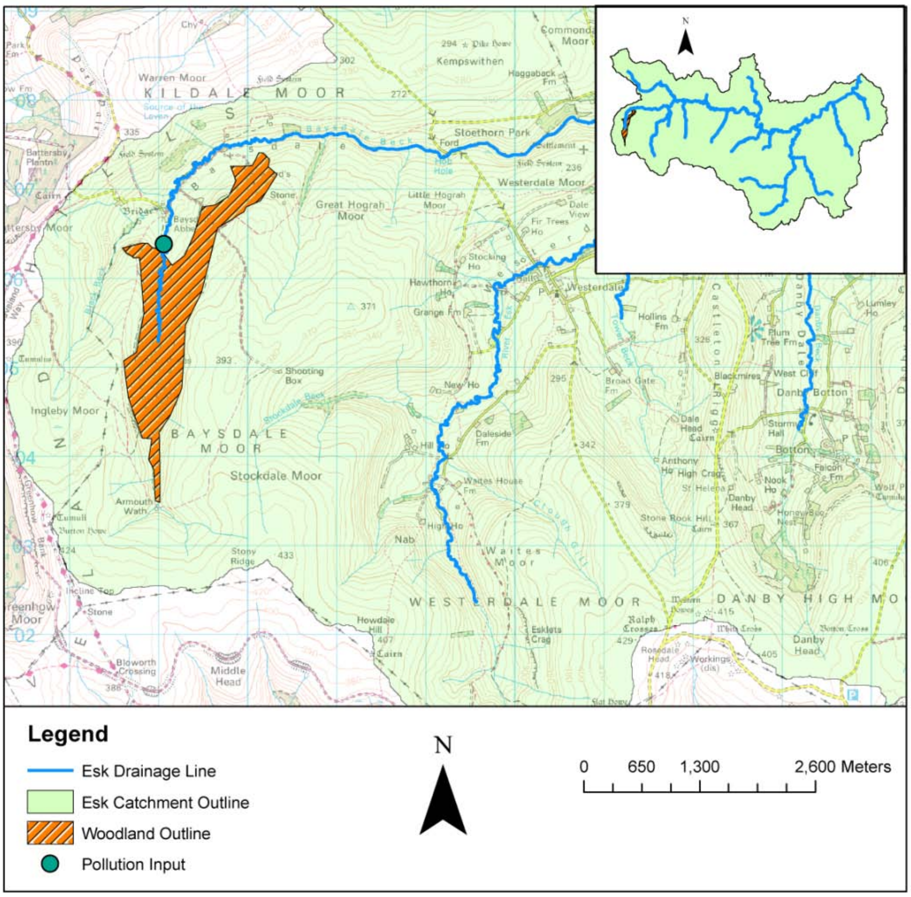


Figure 7.8: Location map of the fine sediment pollution incident in the Baysdale catchment during August 2008

7.3.2 Application of current research: Results from Fine Sediment Monitoring

Data collected during August 2008 at the Danby and Grosmont suspended sediment monitoring stations in presented in Figure 7.9. This diagram shows a period of multiple sediment transfer events with the most notable taking place on the 19th August 2009, where SSCs reached 516.1 mg L^{-1} and 470.1 mg L^{-1} at Danby and Grosmont on the Esk River respectively. This is not unusual given the meteorological forcing at this time (Section 6.2 and 6.3).

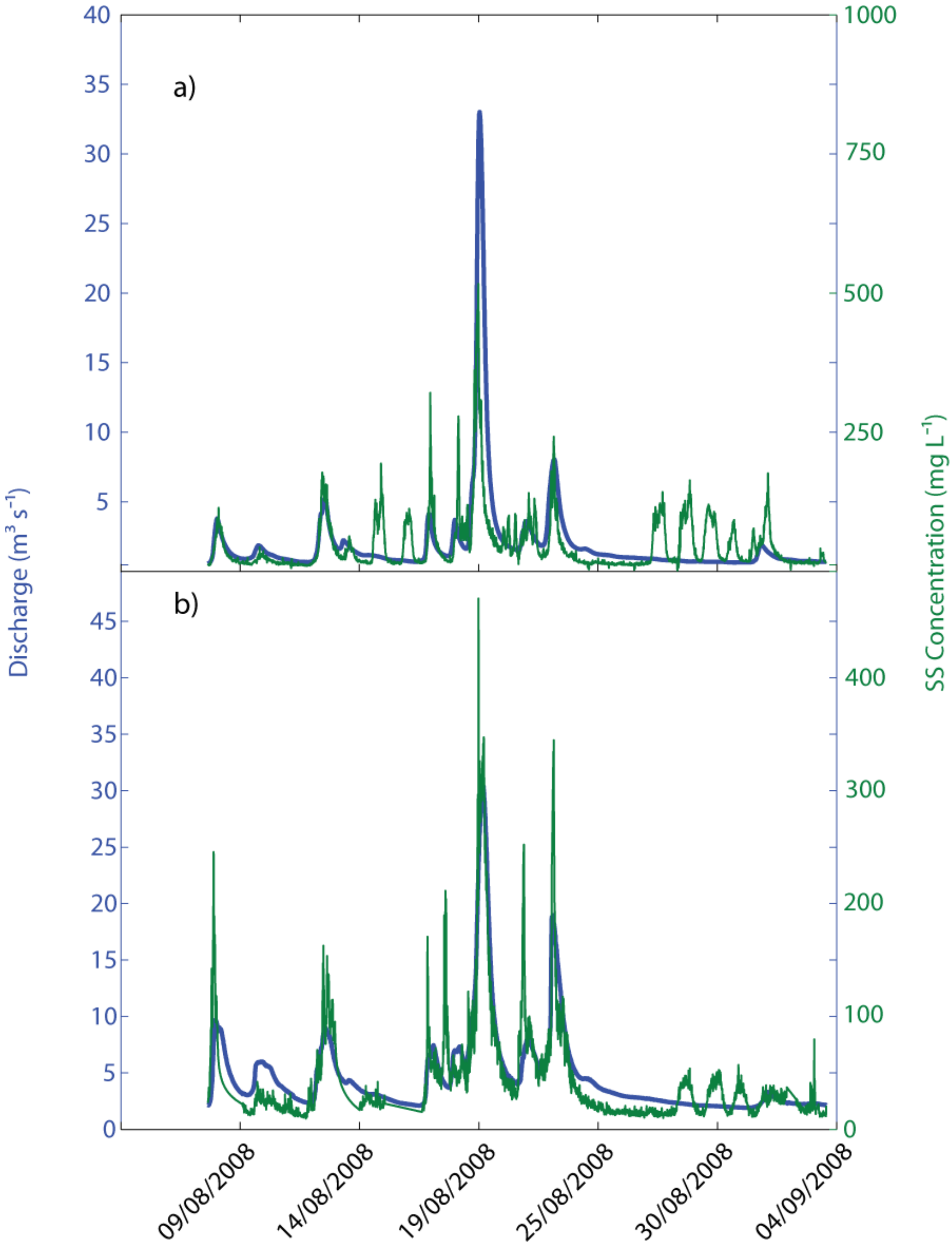


Figure 7.9: Data from the turbidity monitoring stations at **(a)** Danby and **(b)** Grosmont on the River Esk between 9th August and 4th September 2008

Of interest during this period is the occurrence of sediment transfer events under base-flow conditions. Transport events under these conditions are seldom seen in the Esk catchment but can be observed at Danby on the 15th, 16th, 27th 28th, 29th and 30th August 2008. Between the 16th and 25th is a period of pronounced rainfall and subsequent high flows which make it difficult to differentiate between storm inputs and inputs from logging activity, although the latter will inevitably increase inputs during this storm activity.

Through analysis of these ‘base-flow events’ the most notable difference is their form; at the time of the logging activity, very abrupt increases in SSCs which have a broad peak followed by an abrupt decrease to background levels. This is presumably associated with the timing of logging work close to the channel and direct inputs to the fluvial system. Also of note is that the turbidity signal is observed at both the Esk at Danby and Grosmont monitoring stations (with the exception of the events on the 15th and 16th due to poor quality data at Grosmont). This suggests that the majority of the sediment mobilised at the time of logging operations is transferred through the upper Esk catchment. Therefore fine sediment does not appear to be stored in the headwater channels but is flushed through the system. This lack of in-channel deposition has also been corroborated by EA fishery officer Andrew Delaney. For this to be possible, the mobilised sediment would have to be very fine. Analysis of the sediment collected on Baysdale Beck by the TIMs indicates a median particle size of the transported sediments to be 15.2 µm, which is indeed relatively fine for these steep headwater tributaries. One could therefore expect minimal ecological effects posed by the smothering of gravels immediately prior to a sensitive time for salmonid spawning.

Additional analysis of the within-storm fine sediment dynamics at the Danby monitoring station over this period showed evidence of 17 sediment transport events which are summarised in Table 7.6. From this summary information it can be seen that the distribution of flow and event load data is positively skewed as illustrated by the mean values being greater than the median, indicating the dominance of small magnitude events during this period.

	Mean [CV %]	Median [MAD]	Min - Max
Danby Q Max ($m^3 s^{-1}$)	4.35 [176.24]	1.94 [1.24]	0.66 – 33.02
Event Load (t)	28.43 [270.84]	5.40 [3.58]	1.00 – 324.46
HI	-0.33 [-364.96]	-0.34 [0.37]	-2.42 – 2.67

Table 7.6: Summary information of the 17 sediment transport events during the period of disturbance in the Baysdale Beck sub-catchment monitored at the Danby monitoring station

These small magnitude events which have been documented do not exhibit much in the way of sediment hysteresis although the mean and median of the HI are slightly negative (Table 7.6). This occurrence is not specific to this time-period; low magnitude events have been associated with limited hysteresis throughout the monitoring period. During this period of disturbance, there is one relatively large event which begins on the 19th August and continues through to the 21st. During this event, the maximum Q and load generated are 33.02 $m^3 s^{-1}$ and 324.46 mg L^{-1} respectively. This event produces the largest of the HI values with 2.67 and exhibits clockwise hysteresis. This is again not unusual for the Esk catchment, with analysis over the complete monitoring period highlighting the presence of sources proximal to the channel.

The sediment transport events under base-flow conditions (presumably as a result of the logging activity) that were measured at the Danby monitoring station occurred on the 15th, 16th, 27th, 28th 29th and 30th August 2008. These events were responsible for a total of 22.14 t of fine sediment being transported past the Danby station (Table 7.7). Unfortunately, due to the distribution of the data i.e. the lack of a rising and falling limb of the hydrograph, it is not feasible to calculate HI values for the sediment pulses.

	Danby HI	Danby Q	Event Load
8th August @ 01:15 – 9th @ 04:45	0.08	3.79	10.16
9th August @ 22:15 – 10th @ 20:45	-0.48	1.87	2.69
12th August @ 12:45 – 13th @ 16:15	0.12	5.30	26.03
13th August @ 18:45 – 14th @ 14:45	-1.48	2.22	3.95
15th August @ 03:15 – 23:45	NaN	1.15	5.41
16th August @ 09:15 – 17th @ 00:15	NaN	0.79	2.52
17th August @ 10:15 – 18th @ 08:45	-0.62	4.13	14.71
18th August @ 16:15 – 19th @ 09:30	-0.89	3.69	13.17
19th August @ 09:45 – 21st @ 14:15	2.67	33.02	324.46
21st August @ 14:15 – 22nd @ 12:45	-0.12	3.60	15.25
22nd August @ 17:45 – 24th @ 02:15	-0.20	8.05	41.94
27th August @ 07:45 – 28th @ 03:45	NaN	0.91	4.72
28th August @ 13:45 – 29th @ 07:15	NaN	0.78	4.14
29th August @ 14:15 – 30th @ 08:15	NaN	0.71	3.53
30th August @ 15:45 – 31st @ 09:15	NaN	0.66	1.82
31st August @ 16:45 – 1st Sept @ 00:15	0.14	1.25	1.00
1st Sept @ 00:30 – 2nd @ 03:45	-2.42	1.94	7.84

Table 7.7: Information about the within-storm fine-sediment transfer occurring at Danby during a period of disturbance in the headwater tributaries of Baysdale during August 2008. NaN represents events where the HI could not be calculated. Pollution (non-flood) driven events are coloured red.

In addition to the high-frequency suspended sediment monitoring campaign, TIMs sampling was undertaken between the 3rd and 30th August 2008 and so captures the entire period of disturbance with an 11 addition days prior to the fine sediment pollution event taking place. The mass flux data generated from this is provided in Figure 7.10. It should be noted that the flux is presented in SSY rather than load. This figure demonstrates that despite the disturbance in the Baysdale catchment, the SSY relative to the adjacent sub-catchments in the headwater of the Esk catchment is not exceptional (0.51 t km^{-2}) compared to Danby Beck (1.42 t km^{-2}) and Commondale Beck (0.62 t km^{-2}). However, it is greater than that measured at Tower Beck (0.22 t km^{-2}).

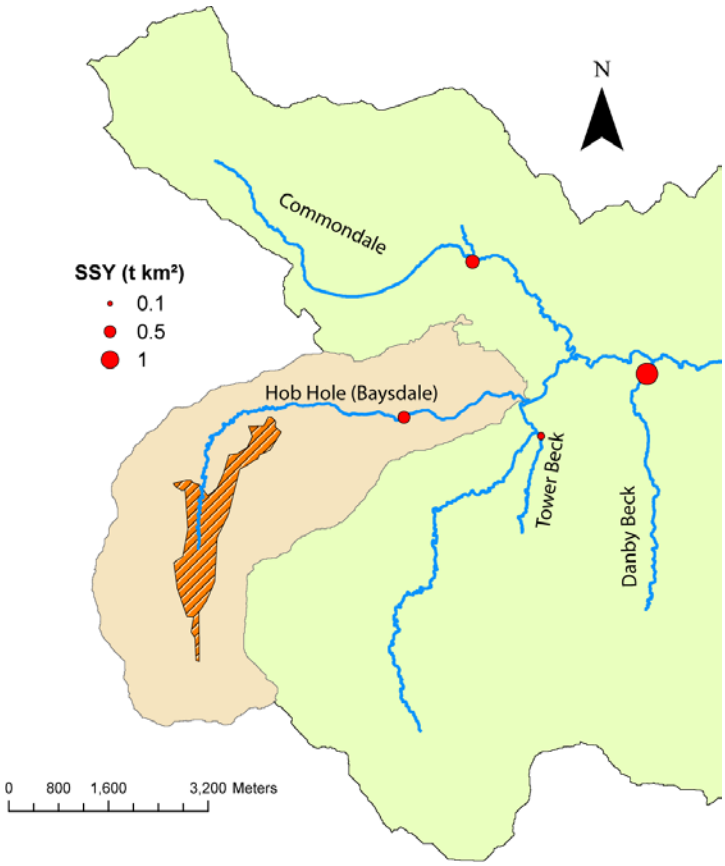


Figure 7.10: Spatial distribution of SSYs in the headwater of the Esk catchment during a period of disturbance in the headwaters of the Baysdale Beck (Hob Hole) catchment between 3rd and 30th August 2008).

Although the SSYs do provide some interesting information on the transfer of fine suspended sediment relative to the contributing area, the fact that the SSY at Hob Hole (Baysdale Beck) is lower than that measured at, for example, Danby Beck is perhaps unsurprising given that the this tributary has been highlighted as having relatively elevated

SSYs compared to other headwater tributaries. In the case of the Esk catchment, the relationship between the SSY measured at Hob Hole and adjacent tributaries is not of high enough precision to allow analysis of the changing SSY ratios to be undertaken. However, in other catchments with less variable suspended sediment transport patterns this would be possible.

This case study highlights the power of utilising high frequency turbidity probes, coupled with low cost time-integrated samplers distributed across an upland catchment to detect the magnitude of observed pollution events. Analysis of the high frequency turbidity data recorded at Danby estimates approximately 22t of fine sediment was mobilised during pollution driven events. However, the TIMs network suggests that despite this incident, the SSY during the monitoring period for the Baysdale sub-catchment was still less than that of Danby Beck.

7.4 CASE STUDY 3: Assessment of Impacts on Habitat Quality and Species

7.4.1 Context and Problem

In the Esk catchment, a main environmental priority has been to return the river habitat to the conditions desirable for the endemic populations of the Pearl Mussel (*M. margaritifera*). Threats to Pearl Mussel populations include pearl-fishing, pollution, acidification, organic enrichment, siltation, river engineering, and declining salmonid stocks (JNCC, 2011). In the Esk catchment the main geomorphological threat to the habitat of these species is thought to be extensive fine-sediment deposition in the Upper Esk catchment.

The Pearl Mussel is one of the most critically endangered bi-valves in the world (Machordom et al., 2003) with fewer than 50 rivers world-wide supporting recruiting populations (Hastie and Young, 2001). These populations have been in decline across central Europe and mainland UK over the last century (Skinner et al., 2003)and is listed on annexes II and V of the EU Habitats and Species Directive and Appendix III of the Bern Convention (Skinner et al., 2003) Surveys in the UK have revealed populations in more than 105 UK Rivers. The majority of which are located in Scotland with only 10 populations in England (Geist, 2010). Most of these populations are functionally extinct, with very little active recruitment (Chesney and Oliver, 1998). The Esk catchment has over 500 pearl mussel individuals present along the main river between Castleton and Glaisdale (Figure 7.10). However, of concern is that the shell size of the population ranges from 96 – 151 mm. This indicates an absence of recent recruitment given that mature adults generally exceed 65 mm (Skinner et al., 2003; Joaquim, 2003). However, there is still potential for recovery of this population due to the longevity of this species i.e. a lifespan of more than 100 years, together with the high reproductive potential even in polluted rivers and at extreme old age (Geist, 2010).

The Pearl Mussel (*M. margaritifera*) has two key life stages when it is most vulnerable. Firstly, adult pearl mussels release glochidia which parasitize the gill filaments of young salmonids which are hosts for between six months and one year. This phase is dependent on the abundant presence of healthy salmonids for which the larvae can attach. Secondly, following detachment of the glochidia, the post-parasitic juveniles must find a suitable habitat, where they will be incubated for up to five years. This is dependent on the presence of boulder-stabilised refugia, which contains clean sand for burrowing (Bolland et al., 2010; Joaquim, 2003). Juveniles are intolerant of fine substratum which can dramatically reduce the interstitial oxygen content (Geist and Auerswald, 2007), whereas adults are less sensitive to the bed particle size composition (Hastie et al., 2000). This species is sensitive to low level chronic pollution, with concentrations of nitrate (> 1 mg L^{-1}) and phosphate (> 0.02 mg L^{-1}) being harmful to the organism (Skinner et al., 2003). Further requirements are cool, fast flowing waters that are low in calcium (Beasley and Roberts, 1999). Recruiting Pearl Mussel populations are a key indicator of a healthy river system.

Therefore, several key targets have been developed to ensure adequate habitat for this organism; (1) Ensure a healthy population of salmonids; (2) Prevent excessive siltation of river beds; (3) Minimise diffuse agricultural pollution and point sources.

7.4.2 Management Action

Much of the work up to 2001 to meet broad targets above was carried out under the guise of the River Esk Regeneration Programme. Working towards this involved; the management of 21km of riverbank, 9km of river channel habitat improvements, stocking of 130,000 native Esk salmon fry, enhanced monitoring of fish and otter populations and the instalment of a fish weir at the gauging station at Sleights (Arnold-Forster, 2002).

Following the end of this project, subsequent management strategies have been adopted, namely through the River Esk Pearl Mussel and Salmon Recovery Project (EPMSRP). In order to target areas of the catchment where mitigation would provide demonstrable improvements to the declining habitat, a substantial evidence base (outlined below) has been acquired:

- Spatially extensive sampling of the current water quality of the river with particular reference to fine suspended sediment flux; dissolved anions and cation concentrations.
- A river corridor survey along 25km of the river Esk and its tributaries (as of 2008), to identify evidence of areas with bank erosion, water quality issues and sources of fine sediment within the catchment (Figure 7.11).

- This same survey also searched for evidence of current Pearl Mussel populations. 578 individuals were found along a 13.8km reach between Castleton and Glaisdale (as of August 2010) (Figure 7.11). None were found in the tributaries.

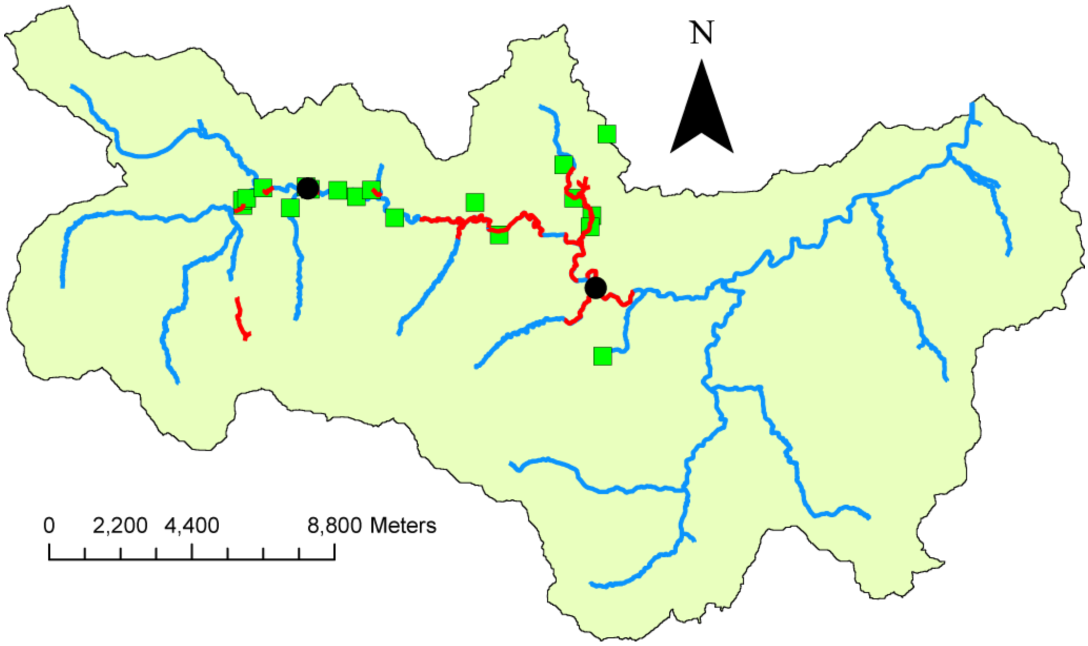


Figure 7.11: Map identifying the areas of the river corridor survey (red lines) and river restoration work (green square) conducted by the NYMNP. The black circles represent the upper and lower limits of the Pearl Mussel populations along the main Esk River.

Throughout the duration of and following the results of these monitoring programmes and surveys, the following remedial works in the catchment have been carried out:

- River restoration work at 27 sites, including the stabilisation of river banks deemed at risk of erosion. This was achieved through fencing 20.5km of river banks, planting 1170 trees, grass seeding, creation of buffer strips, funding of 7 stock crossing points and 4 stock watering points (Figure 7.11).
- Re-routing of upland watercourses (i.e. Glaisdale Beck) where the route of the river is causing excessive erosion and high rates of fine sediment delivery to the channel.

- Creation of a demonstration farm to demonstrate good environmental practice and highlight ways of protecting the river from sediments and other pollutants.
- Proposed work is targeting fencing of an additional 9.8km of river banks, planting 1120 broadleaved trees and the creation of 1 silt trap and 1 cattle crossing point.

In addition to these achievements, some of the Pearl Mussels deemed to be vulnerable were moved to a specialised ark facility in 2007 in an attempt to safeguard the current population. It is planned that these will be re-introduced back to the river Esk from 2013 onwards. The removal of the vulnerable Pearl Mussels represents an important step in the management of the river Esk; creating pressure to ensure that pearl mussel habitat is suitable for release of the organisms. Before restocking can occur, it must be deemed that the habitat conditions are suitable for all life stages of M. margaritifera (Bolland et al., 2010).

7.4.3 Application of current research: Results from Fine Sediment Monitoring

At the most fundamental level, suspended sediment monitoring at the Danby and Grosmont monitoring stations on the Esk River have provided background information on the quality of the River Esk with regards to fine suspended sediment. This information is summarised in Table 7.8.

	Mean (mg L^{-1}) [CV%]	Median (mg L^{-1}) [MAD]	Min & Max (mg L^{-1})
Esk at Danby	25.43 [188.59]	12.66 [4.34]	0.07 – 827.95
Esk at Grosmont	24.35 [213.21]	9.88 [3.99]	0.09 – 953.19

Table 7.8: Summary suspended sediment concentration information for the Esk at Danby and Grosmont

This information is imperative for assessing the quality of the river and determining the status of the river with respect to legislation targets and the suitability of habitats for protected species. Cooper *et al.* (2008) provide a critical threshold in terms of SSC in which the average which does not exceed 25mg L^{-1}, whereas Stutter *et al*. (2008) suggest a threshold of 10mg L^{-1} for rivers sustaining Pearl Mussels. The data presented in Table 7.8 highlight that the mean SSCs at both monitoring stations are comparable to the critical threshold suggested by Cooper *et al*. (2008), but far exceed the threshold of 10 mg L^{-1}. Figure 7.12 shows that this 10 mg L^{-1} threshold is exceeded 72.7% of the time at Danby and 49.25% at Grosmont. This indicates that for considerable proportions of the year, the suspended sediment conditions are not conducive to maintaining healthy habitat for Pearl Mussels. Conversely, the 25 mg L^{-1} threshold is only exceeded 28.74% of the time at Danby and 18.87% at Grosmont. The implications of these findings are that the conditions of the River Esk are currently unfavourable for the Pearl Mussels providing a possible explanation for the observed low recruitment rates. Furthermore, the reintroduction of individuals (previously removed to safeguard the population), back into areas deemed unfavourable for the species be viewed as placing the species at risk and therefore be in contravention of their protected status.

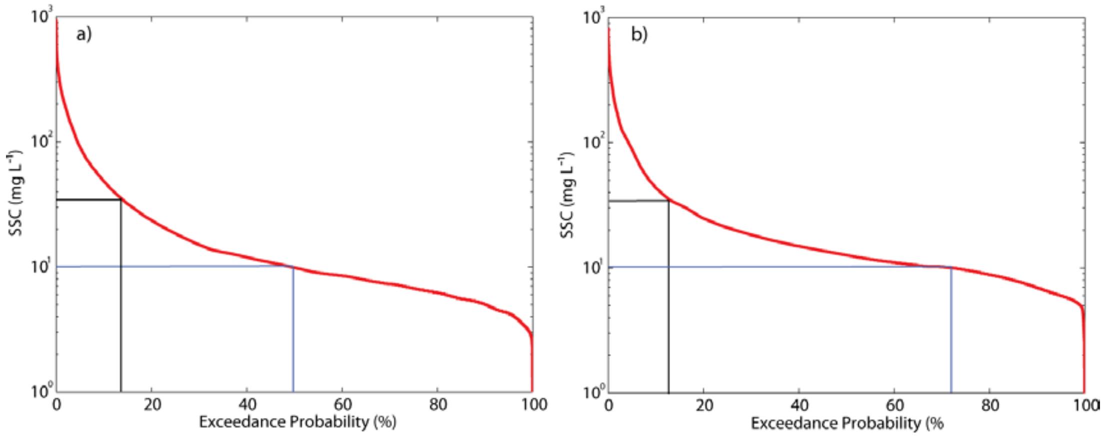


Figure 7.12: Graphs displaying the exceedance probability of 10mg L^{-1} (blue line) and 25mg L^{-1} (black line) for the; **(a)** Esk at Danby and **(b)** Esk at Grosmont. Note log scale on Y-axis.

Suspended sediment monitoring using the spatially extensive network of TIMs has also allowed the catchment response to be characterised over several seasons, highlighted broad-scale areas of relatively high fine sediment transfer, key zones of potential sources and the physical characteristics of the transported material (Chapter 5), which can be used to target areas in the catchment which would potentially benefit from future remedial action. It has also been proposed that TIMs *"provide an effective approach for identifying* ***river reaches*** *with low levels of fine sediment transport that are likely to be suitable for M. margaritifera"* (Bolland et al., 2010). However, at the reach scale, areas of low flux do not necessarily relate to areas which are likely to sustain favourable habitat conditions. For example, it has been shown that the bed infiltration rate for a given sediment transport rate decreases as total sediment flux increases. That is, the transported fines can infiltrate areas of the bed with low levels of accumulated sediment more readily than areas where high fluxes have previously plugged many surficial interstices (Lisle and Lewis, 1992). It therefore follows that suspended sediment flux may be a poor metric for habitat quality when used alone (Newson et al., 2008). At a reach scale it is more appropriate to conduct additional assessments of river bed composition and mapping of channel conditions (e.g.

depth and flow) in order to assess areas within the watercourse deemed favourable for re-stocking.

7.5 CASE STUDY 4: Bench-marking risk-based diffuse pollution models using fine sediment flux data: application of 'Sensitive Catchment Integrated Modelling Analysis Platform' (SCIMAP)

7.5.1 Context and Background

Section 2.8 describes the difficulties in developing cost-effective sampling strategies to determine suspended sediment flux throughout UK catchments. Progress in attaining necessary information to assess fine sediment transport has been limited. This is of paramount importance in identifying when non-compliance with water quality standards is occurring. In contrast to this, our increased understanding of the active physical processes involved in the generation and delivery of diffuse pollutants such as fine sediment means that the development of modelling applications in a GIS framework to predict fine sediment transport has become a reality.

Recent approaches have focussed on modelling fine sediment delivery and transfer at high resolution (< 100m^2) but over extensive spatial scales (i.e. 100 – 10,000 km^2). The spatial complexity of sediment mobilization and transfer over this kind of catchment scale requires a distributed approach to modelling (Collins and Walling, 2004). A recent example of such models is that developed by Collins & Anthony (2008b). They modified the physically based, phosphorus and sediment yield characterisation in catchments (PSYCHIC) model to incorporate predicted losses from urban areas, eroding banks and point source discharges. Such models utilise the combination of landscape attributes and land management practices to identify areas of highest pollution risk (Davison et al., 2008). These models can be easily replicated regionally or nationally with relatively low data input requirements, thereby providing a useful tool for assessing the likelihood of meeting water quality targets and for assessing the potential effectiveness of land use modifications to control issues of fine sediment pollution.

SCIMAP adopts a risk-based approach whereby human activities (e.g. fertiliser input) and geomorphological controls (e.g. soil type, local slope) are combined to create a risk of fine sediment being transported from the land to the watercourse (Reaney et al., 2011). In the version of the model utilised here, modification of the landscape is assessed through the use of the CEH Land Cover Map (LCM) 2000 whereby each land use class is assigned a unique risk weight. The subsequent geomorphological requirement of connectivity between a potential source and the watercourse is achieved using a network index approach (Lane et al., 2004). Whereby the topographical wetness index, defined as $\ln(a/\tan\beta)$ whereby a is the local upstream area and $\tan\beta$ is the local slope is used to predict the relative wetness across the catchment (Beven and Kirkby, 1979). This is a time-average approach that implicitly contains a temporal component as locations in a catchment that are more difficult to connect in space are also connected for shorter durations (Milledge et al., 2011).

7.5.2 Application of current research: Results from Fine Sediment Monitoring

This risk based mapping tool operates with a similar underlying philosophy as the TIMs spatial monitoring framework. Both tools seek to answer the same question i.e. given a river showing evidence of enhanced sediment transfer, which areas of the catchment or sub-catchment are most likely to be responsible for its creation? (Lane et al., 2006). In order to answer this, diffuse pollution sources are determined with respect to one another in terms of their *probable relative importance* (Lane et al., 2006). The model outputs highlight the spatial variability of fine sediment risk across the channel network, which can then be examined in further detail to determine which areas of the catchment warrant additional attention either in terms of monitoring, or direct intervention. These outputs are provided in Figure 7.13. From this it appears that despite a reduction in topographical forcing risk, generally increases with distance from the source with the very headwaters of the catchment being broadly low risk, with risk increasing downstream as small networks of relatively high risk become connected to the river network, acting to elevate the risk along the tributaries. The concentration of this risk acts to increase the estimated risk in a downstream direction along the main Esk River.

Given there are similarities in outputs (i.e. relative risk) between the TIMs framework and SCIMAP modelling platform, it seems reasonable that the spatial pattern of TIMs yield could be used as a cost-effective tool in the assessment of risk-based fine suspended sediment transport models and specifically to inform of the effectiveness of SCIMAP. Such time-integrated data is required during the development stages to assess predictions (Lane et al., 2006), which cannot usually be met given the cost of assessing that spatial variability across whole catchments. The relative risk of fine sediment transfer at each of the monitoring locations in the Esk catchment as estimated by the SCIMAP model are compared with the outputs from the time averaged (yr) sediment yield (t km^{-2}) generated by the TIMs (Figure 7.14).

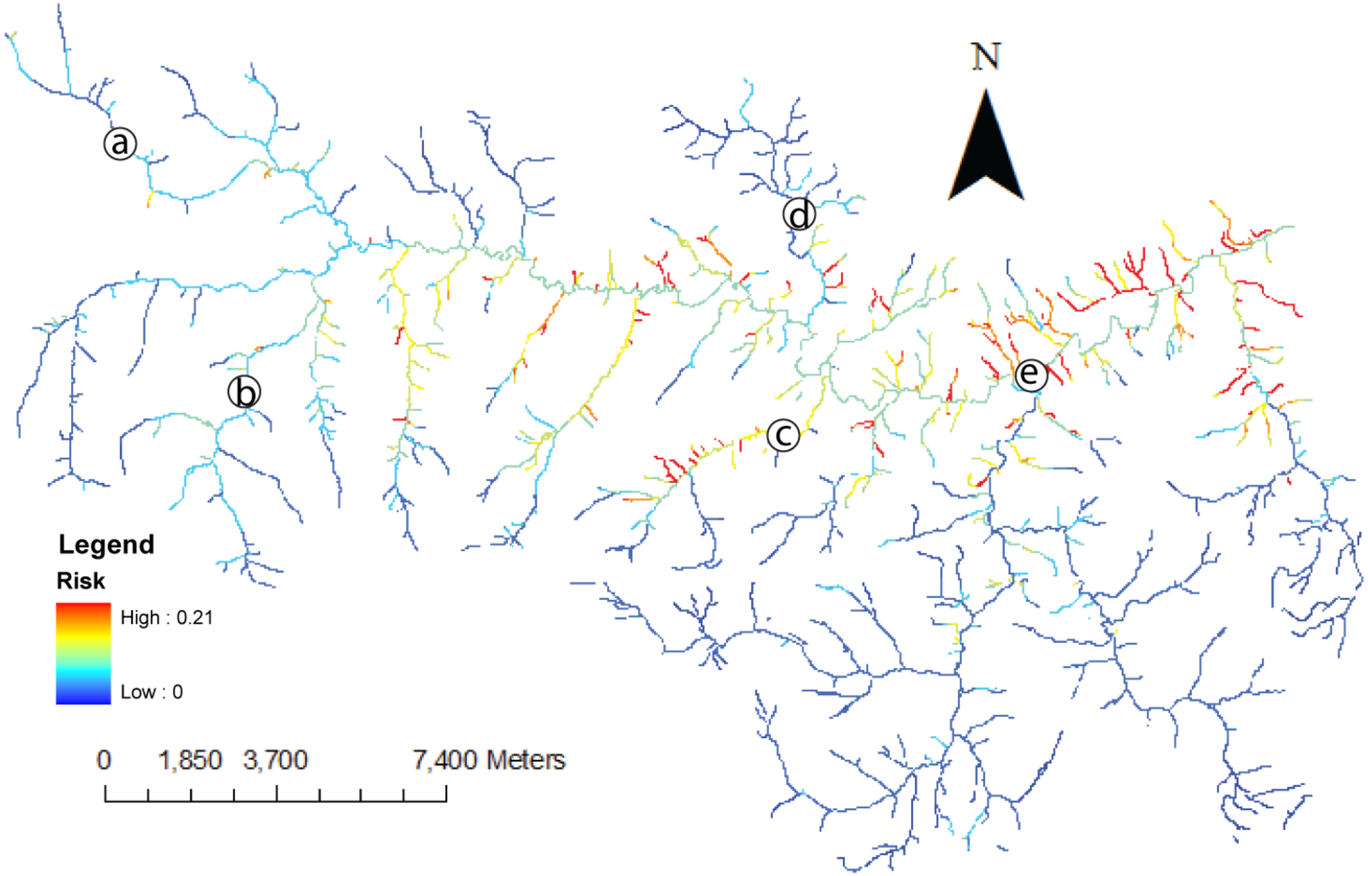


Figure 7.13: Output from the SCIMAP model of fine sediment risk in the Esk catchment. Symbols representations: a) Commondale Beck; b) Westerdale; c) Glaisdale Beck; d) Stonegate Beck; e) Grosmont

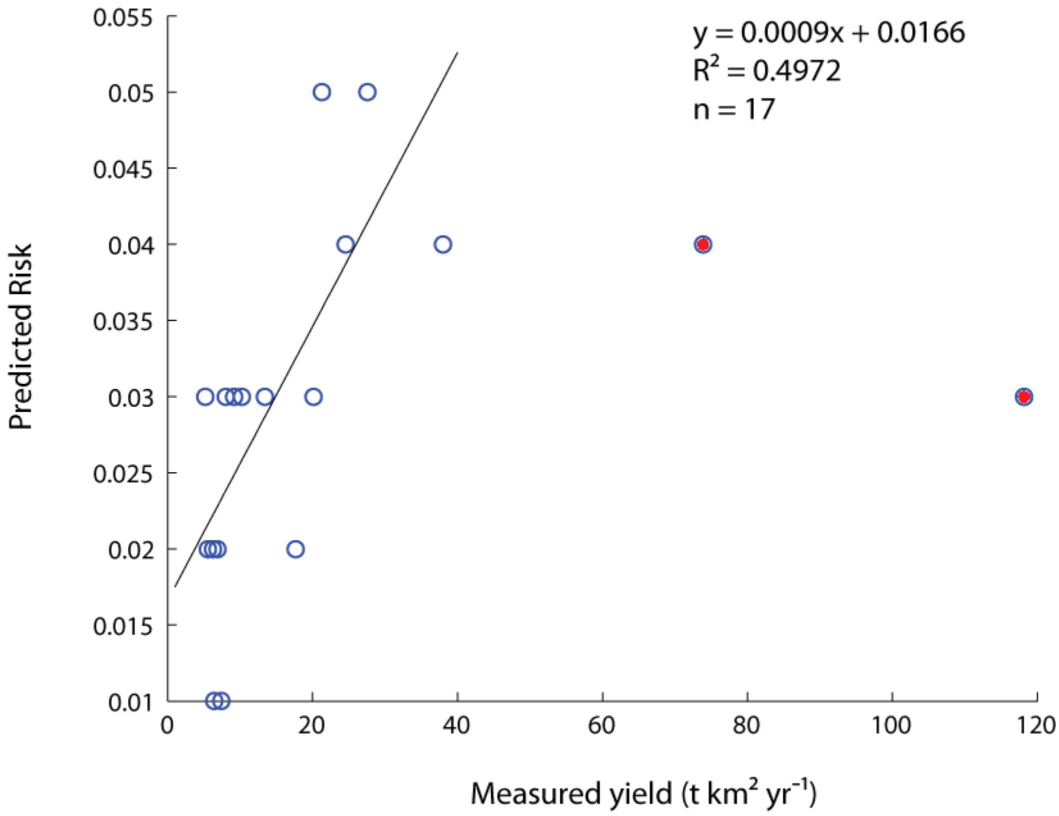


Figure 7.14: Bi-plot demonstrating the relationship between area-specific sediment yield (generated by the TIMs) and the predicted risk (by SCIMAP) at each of the monitoring locations. Outliers and coloured red

Broadly, there appears to be some similarity in response between the two variables (R^2 = 0.50). However, the data generated by the TIMs at Butter Beck and Glaisdale Beck sampling sites was extremely divergent from the SCIMAP predictions. Butter Beck has already been highlighted as having very high relative yields, which is believed to be a result of the removal of woody debris from the main channel. Glaisdale Beck has also been highlighted to have relatively high yields. However, in this case it is likely a result of the continued disturbance following channel straightening. Due to these two confounding factors, these two sites were removed prior to analysing the effectiveness of the model. These findings demonstrate that although models such as SCIMAP may be able to broadly characterise the suspended sediment risk based on land use and connectivity across the landscape, local factors such as catchment management are unlikely to be captured thereby leading to the under or over estimation of risk.

7.6 Chapter Summary

This chapter has demonstrated how a combination of low tech TIMs and high frequency suspended sediment sampling can provide detailed temporal and spatial information about dynamic sediment transport regimes in upland rivers of the UK which can be used to directly assess a range of real-world issues such as (1) the effectiveness of upland channel diversion and assess the stability of the channel; (2) assess the magnitude fine sediment pollution during a period of environmental stress in the headwater catchments and determine the relative change in the magnitude of flux during this period; (3) assess the degree to which upland rivers are meeting legislation and guidelines aimed at creating good ecological conditions and determine the length of time in-stream fauna is subject to potentially detrimental conditions and; (4) generate distributed information on the relative flux of fine sediment throughout a catchment which could be beneficial in testing risk-based models of fine sediment delivery.

Chapter 8: Discussion & Conclusions

8.1 Scope of chapter

This chapter summarises how fluvial suspended sediment monitoring undertaken in this research may be used to inform and develop monitoring programmes, management activities and fluvial geomorphology. A summary of the key findings of this research are outlined with along with identification of limitations of approaches, recommendations for future research, implications for erosion management in the Esk, Upper Derwent catchment and beyond.

8.2 Summary of sediment transfer in the Esk & Upper Derwent catchments

A distributed network of 45 TIMs were deployed throughout the 2007/08 and 2008/09 hydrological years in the Esk catchment and from July 2008 to the end of the 2008/09 hydrological year in the Upper Derwent catchment.

In the Esk catchment, suspended sediment loads (t) generally increase with catchment area. The magnitude of increase scales well with catchment contributing area resulting in a consistent SSY-A relationship, indicative of a system where hillslope contributions do not dominate (de Vente et al., 2007). This suggests that sources from within (and proximal) to the channel dominate or that inputs from tributaries in the lower reaches are important. In the tributaries of the River Esk, peak SSYs occur in the sub-catchments of the central Esk valley such as Butter Beck, Glaisdale Beck and Great Fryup Beck. Smallest SSYs are measured in the tributaries draining the headwater catchments to the west of the catchment such as Tower Beck and Baysdale Beck (Hob Hole). Areas of relatively coarse suspended sediment are distributed throughout the Esk catchment at Baysdale Beck (Hob

Hole), the Esk at Westerdale, Stonegate Beck and the Esk at Danby. Temporally, the median particle size of transported SS exhibits a strong positive relationship with river flow. Increases in flow facilitate the transport of larger particles. The mean organic content across all sites in the Esk is 13%. This is at a level typical for British Rivers (Walling and Webb, 1987). There is clear evidence of seasonality in the proportion of organic content transported with the maximum occurring during the summer months.

In the Upper Derwent catchment along the main River Rye, suspended sediment loads (t) generally increase with contributing area. The magnitude of increase is again roughly proportional to the catchment contributing area resulting in a fairly consistent SSY-A relationship, indicating the continual mobilisation and delivery of fine sediment down the valley. Along the tributaries of the River Rye, peak SSYs occur in Hodge Beck whereas the minimum SSY is observed at Pickering Beck with sub-catchments draining the catchment to the south of the Rye producing relatively low SSYs. The headwater tributaries of the Upper Derwent catchment also produce moderate to low specific yields. Areas of relatively coarse suspended sediment are limited to the headwater tributaries with evidence of significant downstream fining but little/no evidence of seasonal variability in the median particle size of sediment transported. The organic content of sediment transferred through the sub-catchments draining agricultural catchments is maintained at relatively stable and high levels. Organic content in headwaters is also moderate (median of 18%). The smallest proportions were obtained at Blow Gill, Rye at Church Bridge and Hodge Beck (median < 10%). No discernible seasonal patterns in organic content were observed.

At Danby (Esk - upper), the mean SSC of the 2007/08 and 2008/09 hydrological years were 26.67 and 24.13 mg L^{-1} respectively with annual sediment loads of 5545.5 (± 1136.1) t and 5425.1 (± 1111.6) t, equating to 57.91 (± 11.87) t km^{-2} and 56.66 (± 11.61) t km^{-2}. Periods of highest SS transfer occur in autumn (2194.7 t), summer 08 (2124.6 t) and winter 08/09 (1793.2 t). Sediment availability is at its minimum under low flow conditions during winter 2008/09 whereas it is at its greatest in the summer months of 2008 and 2009. SS responses to increases in flow are dampened in summer months but heightened during spring. Evidence indicates high inter-annual variability in the SSCs for a given discharge highlighting the complex control over sediment production, depletion and transfer at varying times of the year. Infrequent events are responsible for the transfer of a considerable mass of sediment (e.g. 25% of annual load) in a very short period of time (e.g. under two days). The mass of transferred material can be predicted using event peak discharge (R^2 = 0.89) and total event rainfall (R^2 = 0.25). Of the 82 flow events, 44% exhibited clockwise hysteresis which produced loads significantly greater than all other types of hysteresis events and 15 times more sediment than was transferred during anti-clockwise events. Anti-clockwise events were also relatively infrequent (22%). The hysteresis characteristics indicate that sediment is predominantly transported from within-channel sources and areas proximal to the channel. Maximum rainfall intensity and total rainfall are also greater for clockwise events than anti-clockwise hysteresis events. The magnitude of hysteresis can be predicted using event maximum discharge (m^3 s^{-1}) (R^2 = 0.28) and the event rainfall total (mm) (R^2 = 0.24) as predictor variables, although the strength of these relationships is low.

At Grosmont (Esk – lower), the mean SSC of the 2007/08 and 2008/09 hydrological years were 26.13 and 24.05 mg L^{-1} respectively with scaled annual sediment loads of 13 263.0 t yr-1 (46.28 t km^{-2} yr^{-1}) and 12 249.0 t yr^{-1} (42.74 t km^{-2} yr^{-1}). Summer and autumn 2008 are responsible for the largest proportion of fine sediment transfer, transporting 5341.5 and 5872.3 t respectively. Sediment availability is at its minimum under low flow conditions during winter 2008/09 whereas it is at its greatest in summer 2008. SS responses to increases in flow are relatively dampened in summer months but heightened during Winter

2007/08 and 2008/09. Evidence indicates high inter-annual variability in the SSCs for a given discharge highlighting the complex control over sediment production, depletion and transfer at varying times of the year. Infrequent events are responsible for the transfer of a considerable mass of sediment (e.g. 38% of annual load) in a very short period of time (e.g. under two days). The mass of transferred material can be predicted using event peak discharge (R^2 = 0.96). Of the 66 flow events, 45% exhibited clockwise hysteresis, accounting for 88% of the total load. These events produced loads significantly greater than all other types of hysteresis events and a median load 3 times greater than that transferred during anti-clockwise events. Anti-clockwise events were relatively infrequent (27%) and only account for 13% of the total event load. This indicates that sediment is also predominantly transported from within-channel sources and areas proximal to the channel.

At Broadway Foot on the Rye River (Upper Derwent), during the complete 2008/09 hydrological year, the mean SSC was only 13.87 mg L^{-1}. Annual sediment load was 4437.0 (± 853.68) t, equating to a SSY of 33.92 (± 6.53) t km^{-2} yr^{-1}. Periods of highest SS transfer occur in Autumn 08 and Summer 09. Monthly suspended sediment load (t) follows changes in the monthly water yield reasonably well (R^2 = 0.53). However between August and January, there appears to be a depletion of available sediment sources. June and July represent a period of enhanced availability with low-moderate water yields producing relatively high sediment loads. This has been linked to a sediment preparation phase during the previous four months of low flow. The within storm events during this period indicate the occurrence of multiple processes of sediment generation across the catchment with both hill-slope (June 2009) and within-channel sources (July 2009) dominating the individual periods. Infrequent events are responsible for the transfer of a considerable mass of sediment (e.g. 30% of annual load) in a short period of time (e.g. under four days). Of the 61 flow events, 59% exhibited nearly no hysteresis which accounted for only 38% of the total load. Events exhibiting clockwise and anti-clockwise hysteresis only account for 16.39 % and 18.03 % of the total number of events but transfer a disproportionate mass of sediment i.e. Clockwise events transfer 1793.0 t, with anti-clockwise events transferring 712.33 t which equates to 31.09 % and 12.35 % of the total event load respectively. Sediment sources during low-moderate magnitude events tend to be associated with the delayed transfer of material transferred from the hill-slope and surrounding landscape. However, relatively infrequent clockwise and figure-of-eight (clockwise loop) events transfer a considerable mass of material, which may be associated with sediment being entrained from areas proximal to the river channel. The magnitude of hysteresis cannot be predicted by hydrological variables.

8.3 Implications for erosion management in the Esk and Upper Derwent

At each of the sites monitored, evidence demonstrates high inter-annual variability in SSCs for a given discharge highlighting the complex control over sediment production, depletion and transfer at varying times of the year with infrequent events being responsible for the transfer of a considerable mass of sediment in a very short period of time (e.g. 25% of annual load in less than two days at Danby; Upper Esk).

In the Esk catchment, analysis has highlighted that clockwise hysteresis events produce the largest proportion of sediment load indicating that material is predominantly transported from within-channel sources and areas proximal to the channel. Additionally, spatial patterns of flux showed that the headwater sub-catchments in the West of the catchment have relatively low sediment yields whereas those tributaries draining the south have some of the largest in the area. These findings emphasises the need for a two pronged approach to catchment management with focus on:

(1) Targeting specific sub-catchments in the southern extent of the Esk catchment with the aim of reducing temporary fine sediment storage along the main channel (Figure 5.6).

(2) The within-channel sediment stock could be reduced by targeting eroding river banks and controlling livestock access to the channel (Walling, 2006).

Given the continual high average SSCs throughout the Esk, it is feasible that disconnecting these sediment sources in these areas could lead to significant changes in the suspended sediment regime (cf. Glaisdale Beck channel diversion). However, further work locally through extensive catchments walks and geomorphic surveys would be able to direct resources to specific areas in the sub-catchments (Brookes, 1995a).

The Upper Derwent is generally characterised as having a more restrictive sediment transfer regime, with sediment conditions amenable for good ecological conditions in the River Rye. A great deal of inter-annual variability of suspended sediment flux is observed with analysis of event dynamics highlighting the delayed transfer of material transferred from the hill-slope and surrounding landscape during low and moderate-magnitude events with relatively infrequent events associated with sediment being entrained from areas proximal to the river channel transferring a considerable mass of material. Furthermore, as SSYs patterns demonstrate the continual production of fine sediment available for transfer with increasing distance from the headwater areas, sediment generation and transfer may be described as being temporally dynamic, with distributed sediment sources. However, tributaries draining the area to the south of the River Rye deliver a low mass of sediment to the Rye, given their catchment size whereas tributaries such as the Seph and Hodge Beck to the north produce relatively high sediment yields (Figure 5.19). It is recommended that further work be undertaken to monitor the sediment dynamics of these areas, combined with geomorphological surveys to elucidate potential sediment sources.

8.4 Sediment transfer estimates: Implications for monitoring and geomorphology

SS is a key determinant of 'good ecological status' however, it is not one of the 33 priority physio-chemical substances as defined by the EU WFD and no critical threshold is stated; leading to calls for SS having a higher profile in diffuse pollution policy (Collins and McGonigle, 2008). Despite this limitation in the WFD, there is an implicit assumption that SS will be monitored by authorities in order to both effectively characterise the conveyance of adsorbed constituents which are on the priority list, and also to establish whether sediment conditions encourage 'good ecological status' (Collins and Anthony, 2008a).

Quantifying SS transfer through high resolution, indirect measurements (Chapter 6) has been highlighted as being the most appropriate measure of sediment flux. However, the application of this technology across catchments is often restricted or unfeasible, resulting in many agencies estimating transfer rates based on infrequent sampling protocols which are often biased towards lower flows (Simon et al., 2004). This is particularly the case in flashy catchments where such sampling protocols can at best provide a basic level of characterisation (e.g. EA's WQA). For physio-chemical quality elements, Annex V of the EU WFD recommends sampling be conducted a minimum of four times a year although this is not compulsory (Water Framework Directive, 2000). However, for parameters exhibiting high natural variability such as suspended sediment, where over half the annual load may be transported in 5 or 10 days (e.g. Meade and Parker, 1985), this is unlikely to be sufficient to provide realistic errors and uncertainties of fluxes or even annual average concentrations (Gray, 1999; Etchells et al., 2005; Irvine et al., 2002). The financial costs associated with increasing the sampling frequency of all parameters at a particular measurement site is often the main constraint. Managers would therefore benefit from information regarding the sampling frequency required to generate estimates of: a) sediment flux; and b) average SSCs within an acceptable degree of uncertainty (Strobl and Robillard, 2008). The high frequency SSC data presented in this thesis (Chapter 6) has the potential to be used for this purpose. This is illustrated in the section below.

In order to determine the suitability of a particular sampling interval, SS flux estimates are calculated with fixed sampling intervals ranging from 15 minutes to 219 days, the latter of which would result in the selection of just two samples from the monitoring record. It is assumed that within each sampling interval, one sample is collected at a randomly selected time. In order to use these data to determine suspended sediment flux, several procedures are available. These frequently involve interpolation or extrapolation methods; the latter of which was applied to the dataset with moderate success in Chapter 6. This section therefore focuses on estimating flux using interpolation methods described by Philips et al. (1999) Suggests that the methods which provide greatest accuracy were methods 15 and 18 (cf. Equation 8.1 and 8.2 respectively). Both these methods have been applied to the SS data-series collected at the Broadway Foot, River Rye monitoring station. Owing to the impact of unrepresentative individual SSC-Q pairings which could skew load estimates (Dickinson, 1981), estimates were generated 1000 times to produce a distribution of SS flux (Figure 8.1).

$$SSL = K \sum_{i=1}^{ns} \left(\frac{C_i Q_i}{ns} \right) \qquad \text{Equation 8.1}$$

$$SSL = K \frac{\sum_{i=1}^{ns} C_i Q_i}{\sum_{i=1}^{ns} Q_i} \bar{Q}_r \qquad \text{Equation 8.2}$$

Where K is a conversion factor to take into account the period of record, $\bar{Q}_r$ is the mean discharge for the period of record, C_i and Q_i are the instantaneous values of suspended sediment concentration and discharge, respectively, at the time of sampling and ns is the number of samples.

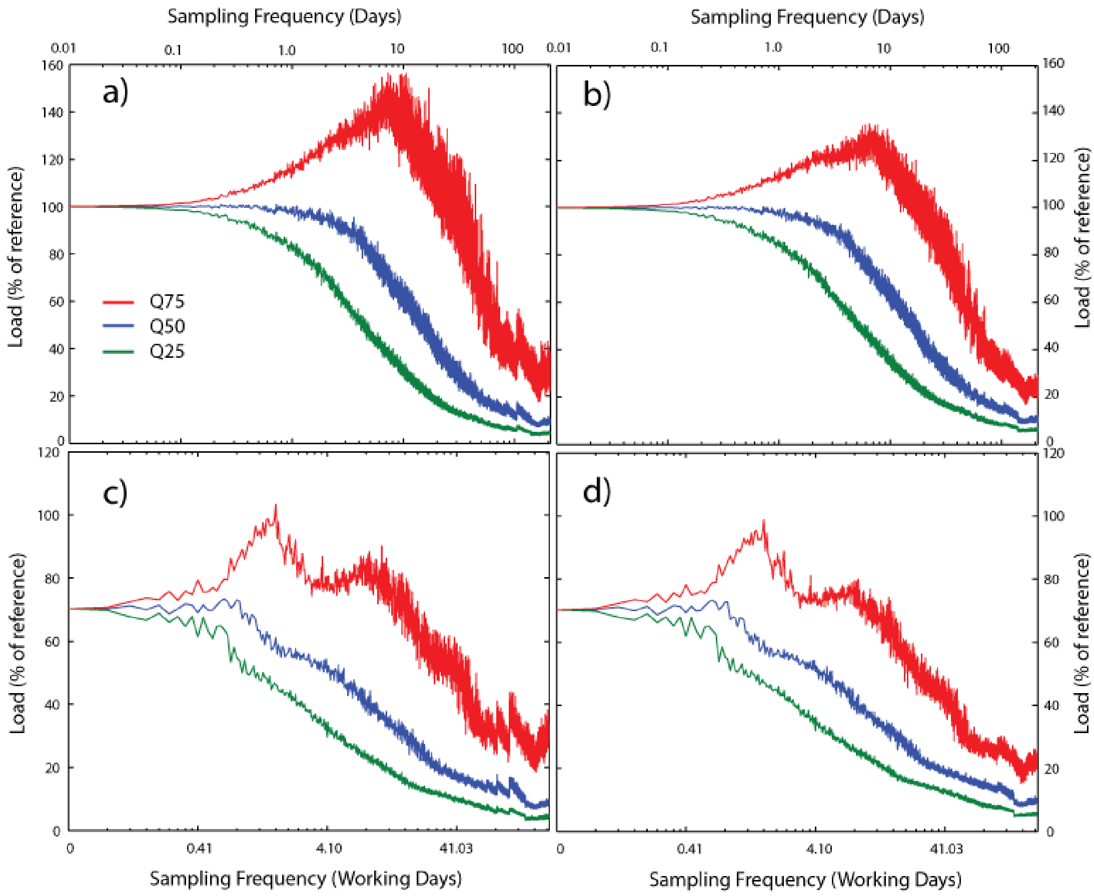


Figure 8.1: Load estimates (as a percentage of reference loads) generated by a range of sampling frequencies using; **a)** model 15 and **b)** model 18 where sampling is not constrained to the working week with **c)** and **d)** representing model 15 and 18 outputs where sampling is constrained to the working week. The Q25, Q50 and Q75 of the model outputs are provided to provide an estimate of uncertainty of the outputs.

It should be noted that the outputs in Figure 8.1 (a – b) are based on the potential to sample at any time during the week. However in practice, when direct, manual samples are taken, it is likely to be impractical to have staff on site during unsociable hours. The model was therefore adapted to add the condition that samples could only be taken between 09:00 and 17:00, Monday – Friday (Figure 8.1 c – d). The results presented in Figure 8.1

demonstrate the necessity of sampling at high frequencies regardless of the interpolation procedure used. Providing that sampling is not limited by the working-week, simulated median sediment loads are within 10% of the reference when SS samples are collected randomly every 3-4 days. However the interquartile (IQ) range of the model runs at this time is 75.9%, highlighting a degree of uncertainty in outputs (for method 15). Weekly sampling would provide a median load estimate which is 70.4% of the reference flux with an IQ range of 106.41%. Monthly sampling would provide a median load estimate 29.0% of the reference flux with an IQ range of 96.24%. This analysis has demonstrated that infrequent sampling at intervals greater than 4 days will generate load estimates which generally underestimate the total load. The observed increase in error with reduced sampling frequency is entirely expected due to the distribution and variance of discharge and SSCs. However of interest is that the IQ ranges (and therefore uncertainty) of model outputs increase rapidly with sampling intervals greater than one-day, with median flux estimates underestimating the true-load. However, over-estimates of up to 159% are found within the IQ range of model outputs. The adoption of sampling protocols responsible for poor estimates may result in inefficient targeting of water bodies, likely justifying extra costs associated with an increased monitoring effort (Carvalho et al., 2005).

The adoption of sampling protocols during only the working week act to reduce potential sampling hours by 76%. This results in the load (as a percentage of the reference load) being greatly reduced even sampling at a 15-minute frequency (during the working week), underestimating the load by 30% (median method 15 model output) with weekly sampling resulting in a median load output 46. 9% of the reference (Figure 8.1 c – d). Therefore in the absence of continuous, or high frequency monitoring, suspended sediment load estimates even using the most efficient interpolation methods still yield poor estimates.

For many agencies, resources may not be available to sample at frequencies capable of generating accurate flux estimates at the national level due to the costs associated with sample collection and laboratory analysis (Littlewood, 1992; Horsburgh et al., 2010). Therefore, a more appropriate descriptor may be mean SSC, which, when compared to total load estimates is less sensitive to the bias imposed by sampling in low flow conditions. This assumption is demonstrated in the model results (Figure 8.2). In this example, a 15-minute sampling interval during the 'working week' underestimates the mean concentration by only 19%. This equates to an underestimation in the region of ~3 mg L^{-1} in this case. Sampling at this frequency would still classify the river as being of 'good' ecological status i.e. < 25 mg L^{-1} (Collins and Anthony, 2008a). However given that the median model outputs are below the actual mean SSC, there is the potential for the bias produced by the sampling frequency to lead to the classification of rivers as 'good' when the actual concentrations exceed the threshold for 'good' ecological status. The simulation using a more typical sampling protocol with monthly samples being collected during working hours would produce a 32.1% underestimation with an IQ range of 50.76%. If there are no time-constraints on monthly sampling, underestimation in the mean concentration could be reduced to 25.09% (IQ range of 70.67%). In order to achieve a sampling campaign producing a median estimate of mean SSC within 10% of the reference, sampling must be conducted at least every 2 days.

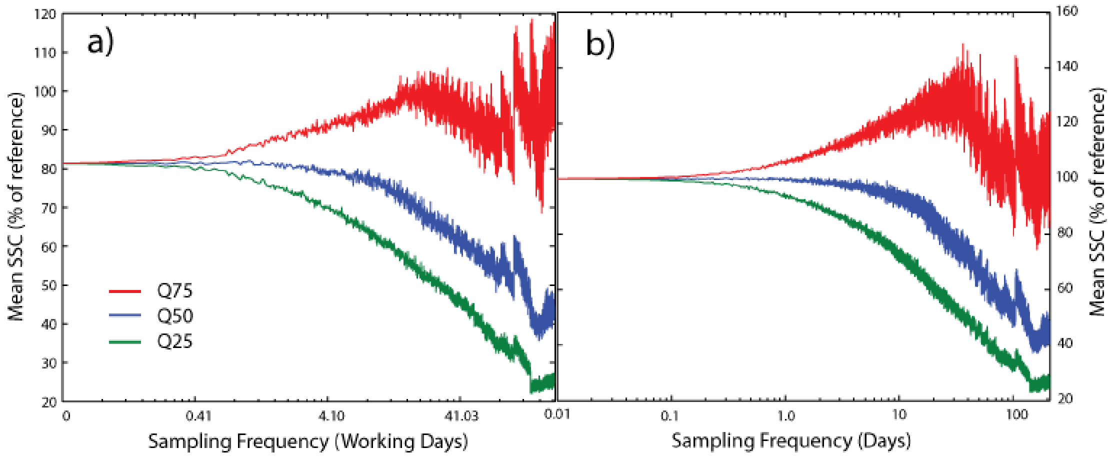


Figure 8.2: Mean SSC estimates generated by a range of sampling frequencies in which sampling; **a)** is constrained to the working week; whereas in **b)** there are no sampling constraints. The Q25, Q50 and Q75 of the model outputs are provided. Note the change in scale between a) and b).

Results are important in providing data to assess whether fluvial systems meet water quality standards (Horowitz, 2008), but also more generally in fluvial geomorphology where sediment loads from different environments are compared (Syvitski and Kettner, 2008; Walling, 1978; Walling, 1984; Jansson, 1988). Examples include studies where anthropological impacts are assessed and sediment budgets developed (Woodward and Foster, 1997; Walling and Collins, 2008) and where mass estimation and temporal precision and accuracy are of paramount importance (Brown et al., 2009). It is important to acknowledge that differences between datasets often owe as much to the incommensurate nature of the measurements as they do to the 'real' differences imposed by the fluvial environments (Horsburgh et al., 2010).

8.5 Low-cost sediment flux estimates: Implications for monitoring & geomorphology

It is important that the results of research into fluvial SS dynamics are organised in a format which is of use to competent authorities. At the regulatory (policy-level) (Caponera, 1992), suspended sediment transfer using internationally recognised methods offers insight into the condition of a river with reference to tangible standards. However, the lack of any explicit suspended sediment concentration/loading standards cited in the WFD is in part due to the high costs of obtaining meaningful spatially distributed estimates of variability in the fluvial network (Brills, 2008). Therefore alongside this need for robust, quantitative measurements is the demand for readily accessible, distributed data on water quality (including suspended sediment) across catchments in order to incorporate suspended sediment into catchment management strategies (Woodward and Foster, 1997).

Although there is a considerable knowledge base of the impacts of changing land-use on the magnitude and timing of erosion within upland catchments, there is a dearth of information about the temporal discontinuity and transfer dynamics of fine sediment through the hydrological networks that drain these areas, with a lack of understanding of scale dependence in sediment yields (Jansson, 1988; Mills et al., 2008). These gaps in understanding have led to calls for the development of frameworks that better characterise spatial variability in fluvial suspended sediment flux and more closely specify provenance of sediment at enhanced spatiotemporal resolutions (Fryirs, 2012; Owens and Collins, 2005; Wainwright et al., 2011). In order to achieve this, new frameworks and monitoring protocols must be efficient and targeted. This brings to the fore the question of whether low-cost devices (such as the TIMs), which are capable of generating approximate data at a large number of sites may have an important role to play in advancing our understanding of how these dynamic systems operate.

Low-cost tools and technologies that are able to deliver appropriate and reliable data have been advocated (e.g. Strobl and Robillard, 2008) with water management authorities tending to seek cost-effective monitoring techniques (Skarbøvik et al., 2012). TIMs offer approximate data that can be easily collected across fluvial networks at low-cost (Chapter 5); they provide an alternative to the current practice of collecting highly detailed data at few sites and may also be used in conjunction with more advanced monitoring systems. Ultimately, a decision based on the project requirements must be made as to whether the benefits of collecting exact data from a small number of sites out-weighs the loss of information which could be gathered through establishing many sites producing approximate measurements (Ongley, 1992). In situations where highly accurate information about specific fine sediment dynamics is required, the TIMs sampling protocol is deemed to be unsuitable. Even with the uncertainty in accuracy and limited capture of the TIMs, the data produced is vital to help to begin understanding spatial variations of sediment flux across catchments, especially in headwater areas which often receive little attention. Current monitoring protocols are not designed to achieve this. The interesting results presented in Chapter 5 underline that we need to either improve the TIMs methodology to reduce uncertainty of sediment capture, or develop alternative approaches to enable better understanding of the spatial and temporal variability of fine sediment fluxes and its properties. This sampling protocol provides a means of characterising the sediment transport regime in addition to identifying areas in the catchment where more targeted monitoring resources may be of benefit and highlighting areas which may respond favourably to mitigation projects (Wilkinson, 2008).

The results of the TIMs validation show that although the TIMs underestimate the actual sediment load of these upland rivers, they potentially operate in a predictable manner. Results from laboratory experiments have previously shown that between 35% and 70% of fine suspended sediment particles are trapped by the sampler with the potential for enhanced sampler efficiency due to the presence of composite particles and flocs in a natural setting (Phillips et al., 2000). Clearly, there is a considerable discrepancy between these laboratory findings and the results obtained during this extensive field monitoring campaign since only 3-9% of the sediment mass being transported in the channel was typically captured. A greater than expected percentage of fine sediment is being lost.

Given these low capture rates, it is imperative that we are confident of the samplers' ability to capture fine suspended sediment at a rate that is in proportion with the ambient sediment flux. This can not necessarily be assumed. Laboratory research has previously shown that there was a highly significant log-linear relationship between ambient flow and inlet flow within the range 15.4 – 58.5 cm s^{-1}. However, outside of this range, turbulent flow structures prohibited the measurement of representative flow velocities with turbulence resulting in a significant decrease in inlet velocity (Phillips et al., 2000). If during the course of a high flow event, the changing effects of velocity and topographical forcing act to enhance the turbulence signature, the intake velocity may be significantly reduced leading to representativeness being questioned. Further research assessing the relationships between ambient velocity, intake velocity and the velocity in the main body of the sampler under a range of flow conditions in the fluvial environment would be beneficial.

The representativeness of TIMs has been shown to be sufficient for geochemical and (most) physical properties in small lowland streams (Phillips et al., 2000; Russell et al., 2000) and this research has demonstrated 'within-site' comparability of sediment properties. However, there are still some significant outstanding issues which should be resolved. These are as follows:

(1) In rivers where the size of the suspended sediment is relatively coarse (> 60µm), vertical variations in both the particle size and concentration of suspended sediment can occur (Guy and Norman, 1970; Schindl et al., 2005). For most sampling sites in the Esk and

Upper Derwent catchments, the median particle size of the transported material is below this threshold (Figures 5.9 and 5.22). However, in the headwaters of the Upper, where fine to coarse sand is transported, there may issues of oversampling of the coarse material, potentially leading to elevated estimates of fine sediment flux and over-prediction in the median particle size. This may be further exacerbated by the positioning of the sampler close to the bed and its non-isokinetic nature (McDonald et al., 2010). In order to assess this, the particle size distribution of a composite sample of sediment collected over the course of multiple events should be compared with that found within the main body of the sampler.

(2) Our current lack of understanding of how sampling efficiency varies within a storm adds to the uncertainty in our description of how the properties of sediment being transported fluctuate. This has the potential to undermine the use of TIMs as a means of source ascription through sediment fingerprinting techniques in locations where catchment erosion and fine sediment delivery to channels is complex with dynamic, multiple sources during the course of an event (e.g. Keesstra et al., 2009).

(3) Blockage of the sampler intake over the course of a sampling period, typically caused by the drift of organic detritus, may dramatically reduce the sampling efficiency of the device. It is not possible to know the duration and timing of blockages which will vary seasonally with changes in organic detritus delivery to the channel and transport within individual floods.

(4) Finally, this research calculated the TIMs flux estimates by scaling the mass of fine sediment collected over the sampling period by the bank-full cross section (divided by sampling cross section of sampler inlet (Section 4.6.1). This provides an approximate scaling

coefficient and allows for the variance in cross sections of flow between sites to be accounted for. These bankfull conditions can occur relatively infrequently in the context of short-term monitoring programmes with typical return periods of 1.1 – 2 years (Dunne and Leopold, 1978) meaning that suspended sediment flux is potentially over-predicted using this method. However, given that the TIMs provide only a relative estimate of flux this may not be a major issue. Further work is possible in developing a scaling factor that could be varied for individual sampling periods. For such an approach to be developed at un-gauged sites it would be necessary to construct/utilise a distributed rainfall-runoff model in order to estimate the varying water volumes per sampling period.

8.6 Process understanding through analysis of sediment dynamics

The fine sediment transfer regime of upland rivers may be characterised as complex, supply-limited systems (Natural England, 2008; Newson and Sear, 2007) controlled by the sensitivity of the catchment to erosion (Evans, 1993) and delivery of material to channels (Fryirs, 2012; Fryirs et al., 2007). These processes result in sediment source areas that are highly variable from daily through to decadal timescales (Walling, 1983) with significant sources that are only accessible when geomorphological thresholds are exceeded during extreme events (Zabaleta and Antigedad, 2012). It is therefore vital to capture the sediment yields and also; information on the changes to sediment transfer time as a consequence of land-use and environmental change (Walling, 2005); timing and magnitude of individual events which can contribute to our understanding of storm suspended sediment fluxes on overall sediment transfer (Smith et al., 2003) and the complex linkages between upstream erosion rates and downstream sediment yields (Walling, 1999).

This research (Chapter 5 & 6) examined the timing and spatial extent of the fine sediment transfer regime which has facilitated: a) understanding of the capacity/availability driven nature of sediment transfer; b) quantification of changes to the sediment regime; c) the linkages between catchment characteristics and sediment yield to be established and; d) appraisal of environmental engineering projects. The synthesis of the fluvial suspended sediment dynamics at the range of temporal and spatial scales also has the capacity to inform about zones of the catchment responsible for generating the observed sediment flux. Additional research could focus on sediment tracing to identify source areas and erosion processes. However the associated costs may limit its application at this catchment scale (Wilkinson, 2008). An additional alternative to more quantitatively assign processes responsible for sediment transfer may be through sediment fingerprinting which has been deployed across several upland catchments (e.g. Hatfield and Maher, 2008; Hatfield and Maher, 2009; Lees et al., 1997; Walling et al., 2001) however; this was beyond the scope of this research.

8.7 Wider implications for erosion management

Recent research has highlighted problems associated with accelerated erosion in upland areas of the UK (Brazier, 2004; Evans, 1997). Estimates suggests that up to 12% of the Scottish upland landscape undergoing erosion (Grieve et al., 1995), with McHugh *et al.* (2002) suggesting that approximately 2% of upland England and Wales has soil degradation issues. Issues of accelerated erosion can be related back to a range of drivers including climate change (IPCC, 2007), increased farming intensity (Tilman et al., 2002), encroachment of human activity, changes in land use and alterations to landscape management (Gordon et al., 2002). Such modifications can produce rapid changes in the magnitude and source of suspended sediment transfer with the short, steep upland rivers draining these environments rapidly conveying supplied material (cf. Burt et al., 1983; Gimingham, 2002; Imeson, 1971; McHugh, 2000; Robinson and Blyth, 1982b). Such processes have been discussed in relation to the catchments studied in this thesis (Chapter 5 and 6).

Attempts to reduce the delivery of this material to hydrological networks are being implemented through national programmes such as Agri-Environmental Schemes (e.g. Environmental Stewardship agreements) and regional programmes such as 'Moors for the Future' and 'Peatscapes' (Evans et al., 2006b; Crowe et al., 2008). For management operations such as these to be successful, a clear policy identifying common strategies, priority target areas and accessible funding routes are essential, alongside a sustained period of monitoring in order to provide a reliable assessment of sediment dynamics (Evans et al., 2006a). In many situations, new long-term catchment monitoring programmes will also need to be established which are capable of: a) capturing the infrequent erosive events that can be responsible for pronounced soil erosion (Renschler and Harbor, 2002); b) assessing the impacts of management practices; c) demonstrating the cost-effectiveness of implementing control measures and; d) convincing local stakeholders of the benefits of implementing improved or different land management practices (Minella et al., 2008). The approaches to fine suspended sediment monitoring adopted in this research are transferrable to other upland catchments, where assessments of the fluvial suspended sediment transfer system need to be undertaken.

8.8 Final Conclusions

This study has investigated the spatial and temporal variability of suspended sediment (and its properties) across two predominantly upland catchments in the UK. The use of TIMs has demonstrated the benefits of a dense spatial sampling network which cannot be achieved using traditional sampling protocols. However, absolute accuracy of sediment fluxes is poor compared to the best indirect techniques for measuring suspended sediment transfer. The hybrid approach of using both high-tech and low-cost approaches for monitoring suspended sediment transfer has allowed a much deeper understanding of sediment transfer and highlighting areas where management may be beneficial. Further research needs to be undertaken to enable better understanding of the ways in which TIMs operate. This research is currently being undertaken as part of the Eden DTC research project (Owen et al., 2012). This is an exciting and on-going challenge for geomorphology with a need to think carefully about the development and adoption of approaches and techniques for process measurement in catchments to meet regulations and further scientific knowledge.

Annex A: Field Validation of Time-Integrated Mass-flux samplers (TIMs)

A1 Background and Context

Despite its widespread application in arctic, temperate and tropical aquatic environments, the determination of the devices' sampling efficiency and representativeness of ambient fine suspended sediment properties has been limited to laboratory experiments (Phillips et al., 2000) and short-term field experiments in small lowland rivers of the UK (Russell et al., 2000) and the arctic (McDonald et al., 2010) (see Section 2.6.4 for a full review of their application).

Given this relative lack of validation work, especially in upland catchments there are significant gaps in our knowledge of the way these sampling devices operate. It is the aim of this section to assess the accuracy, precision and representativeness of the flux estimates and properties of fine sediment measured using these devices. This assessment is conducted over a prolonged monitoring campaign in small and moderately sized upland (sub)catchments with rivers transporting a range of sized material with median particle sizes ranging from 16.63 - 69.43 µm (derived from the TIMs sampler).

This assessment of the TIMs method is achieved in two separate sections. (1) The relative load (TIMs derived) is assessed with reference to the load measured at the monitoring stations at the Esk at Danby, Grosmont, Esk at Glaisdale and Rye at Broadway Foot and; (2) the relative efficiency of suspended sediment load estimates from the TIMs and measured physical and environmental magnetic properties is achieved through the comparison of two samplers located in the same cross-section of flow.

A2 Methods

A2.1 Reference Load Determination

The reference load is assessed using the method described in Section 4.5.

A2.2 Relative Load Determination

The TIMs provide an at-a-point flux which must be multiplied by the cross-sectional area of flow at the time when the sediment was captured to provide a meaningful representation of suspended sediment loads. Given the considerable fluctuations in the cross sectional area of flow over the course of a month, the multiplication factor may pose a source of error in load estimations. However, in order to minimise this, a meaningful scaling factor was approximated by first sorting the instantaneous suspended sediment loads and then producing a cumulative distribution of the values. The discharge for the point at which 50% of the total suspended sediment load was transported was then selected as the scaling discharge value. By reversing the stage-discharge relation, it was possible to determine the river level for this point. Finally, using data derived from detailed EDM surveys, this cross-sectional area for the river could be calculated and then used as the scaling function for the sediment load estimates. This is represented in Equations A1 and A2:

$$TIMs\ SSL = K \cdot M \cdot ScE \qquad \textbf{Equation A1}$$

Where: K = Unit conversion factor; M = Mass of sediment captured (g); ScE = Scaling exponent

$$ScE = \frac{CSA}{ID} \qquad \textbf{Equation A2}$$

Where: CSA = Bank-full cross-sectional area at the point where 50% of load is transported (m^2); ID = Inlet diameter (m^2)

A2.3 Physical and Environmental Magnetic Properties

The particle size and organic content data presented in this chapter has been produced using methods which are consistent with those described in Section 4.6. Additional parameters of magnetic susceptibility and carbonate content are also presented in this chapter in order to test the validity of TIMs sampling on a wide range of physical and geochemical properties.

In order to determine the magnetic properties of the fine suspended sediment samples, a Bartington MS2 Magnetic Susceptibility System was used for analysis. This apparatus is capable of measuring up to 0.1 SI (0.01 CGS) volume specific with a sensitivity of 2 x 10^{-6} SI (2 x 10^{-7} CGS). Prior to analysis the disaggregated material was sub-sampled using a riffle box so that approximately 10 g of sediment was set aside. This sample was then ball milled at 500 rpm for 4 minutes so that the sediment became a homogenous powder like substance in order to eliminate particle size effects (Dekkers, 1997). This material was then placed into a pre-weighed 10 cc pot, which was reweighed (to 4 dp), allowing the bulk density of the sample to be calculated:

$$BD = \frac{M}{V} \qquad \textbf{Equation A3}$$

Where BD is the bulk density (g cm^{-3}), M is the mass of sediment (g) and V is the volume of the container (cm^3).

Immediately before analysing the samples, the apparatus was checked using a calibration standard to ensure that the readings were within ±1% of the control sample's magnetic susceptibility value. When analysing the samples, triplicate measurements were taken at both low (0.47 kHz) and high (4.7 kHz) frequency bands, with the average being taken and used for subsequent calculations. Analysis of the susceptibility at high and low frequencies is important since under low frequency conditions, measurements are largely dependent on the grain size of the measured samples. For example super-paramagnetic grains (< 0.3 µm) have a x_{mslf} value that is up to 20 times higher than samples > 0.3 µm (Dekkers, 1997). Using the high and low frequency magnetic susceptibility values (x_{hf} and x_{lf} respectively), the mass specific high and low frequency magnetic susceptibility (m^3 kg^{-1}) (x_{mshf} and x_{mslf} respectively) are calculated by:

$$x_{mslf} = \frac{\overline{x_{lf}}}{BD}$$ **Equation A4**

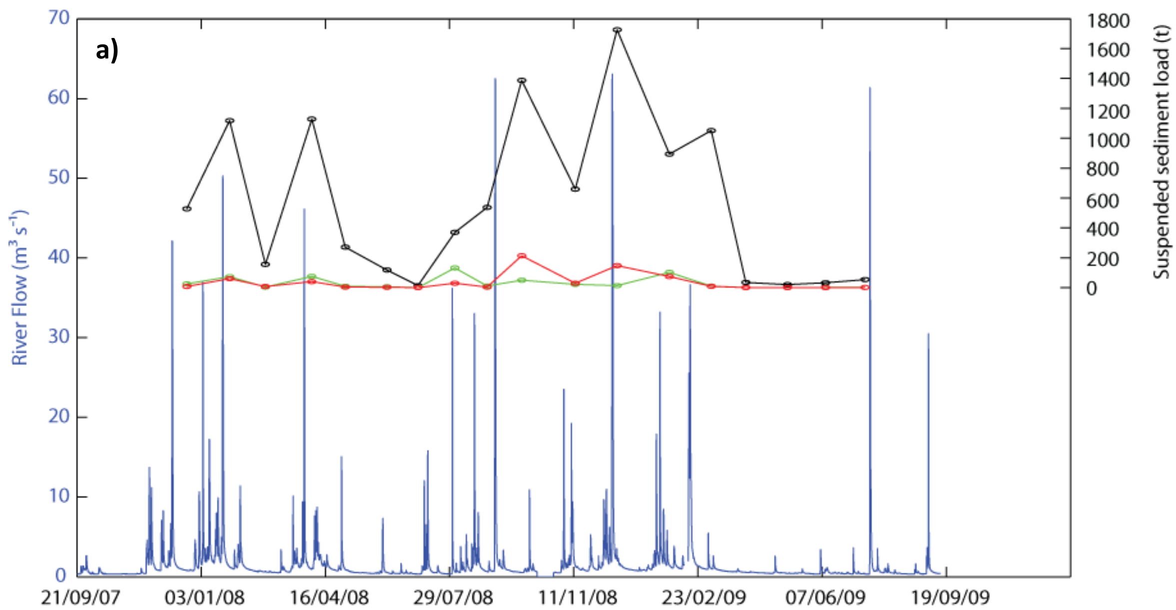
$$x_{mshf} = \frac{\overline{x_{hf}}}{BD}$$ **Equation A5**

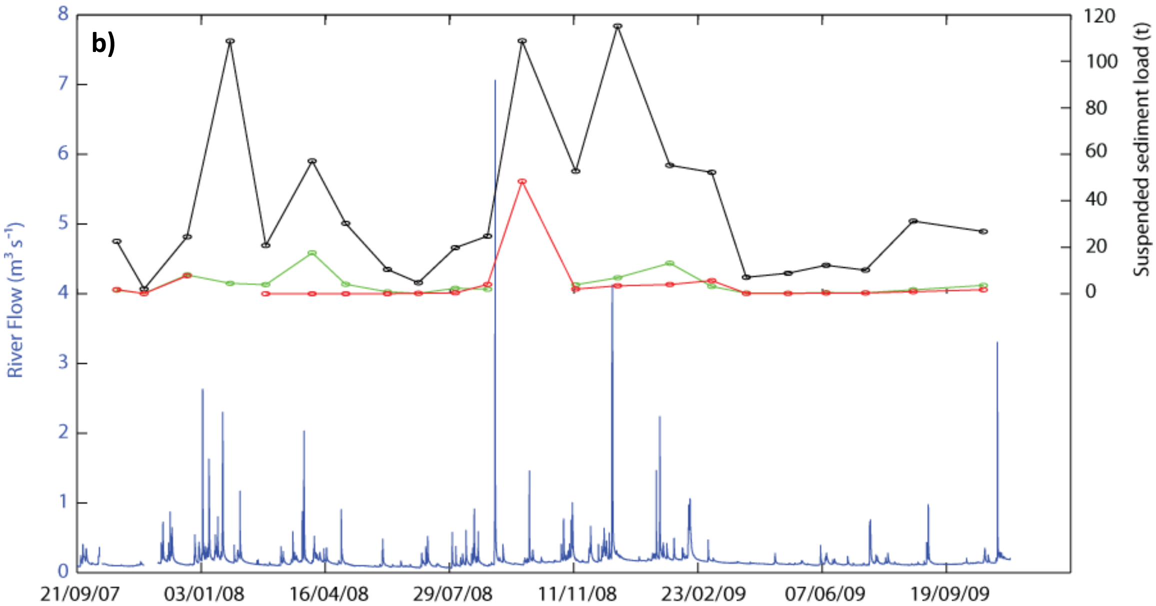
In order to determine the carbonate content of the fine sediment trapped by the TIMs, the sediment was subject to further intense heating following the 550°C ignition which was conducted to determine the organic content. By further heating the material to 950°C, the carbonate present is transformed to carbon dioxide. The weight loss involved in this reaction has been shown to be closely correlated to the carbonate content of the sediment, especially in clay poor material (Heiri et al., 2001). This method is simple and has been shown to provide the precision and accuracy of other, more complex geochemical methods (Dean, 1974). This method was developed following recommendations submitted by Heiri *et al*. (2001) who found that the exposure time and mass of sediment used in the analysis was a critical component of the reliability of the results. Therefore, conditions were constant wherever possible.

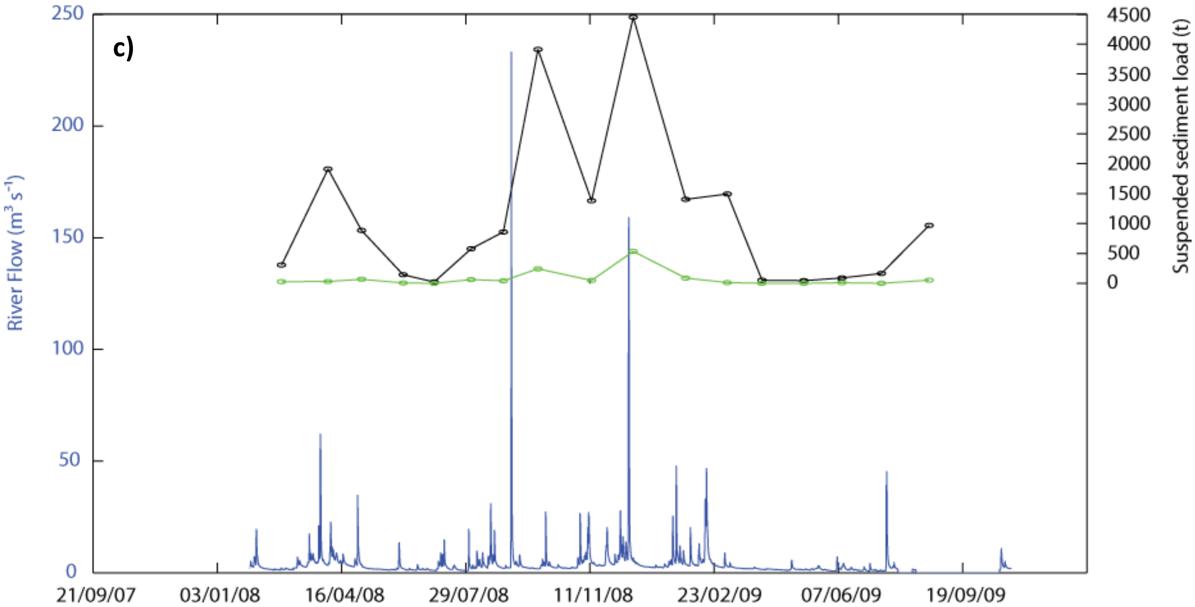
A3 Results

A3.1 Absolute Efficiency of TIMs

The first aspect of TIMs that will be assessed is the efficiency with which fine sediment is captured. To do this the reference load and TIMs load(s) have been calculated for the period spanning from 21st September 2007 to 20th October 2009 for each of the monitoring sites where available data exists. Each data point for the reference and TIMs load(s) is the integration of the sediment load from the time of collection to the previous collection date. These metrics have been plotted along with the observed river discharge for each site with quasi-continuous monitoring in Figure A1 (a – d).




b)
River Flow (m³ s⁻¹)
Suspended sediment load (t)
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100
120
21/09/07
03/01/08
16/04/08
29/07/08
11/11/08
23/02/09
07/06/09
19/09/09


c)
River Flow (m³ s⁻¹)
Suspended sediment load (t)
0
50
100
150
200
250
0
500
1000
1500
2000
2500
3000
3500
4000
4500
21/09/07
03/01/08
16/04/08
29/07/08
11/11/08
23/02/09
07/06/09
19/09/09

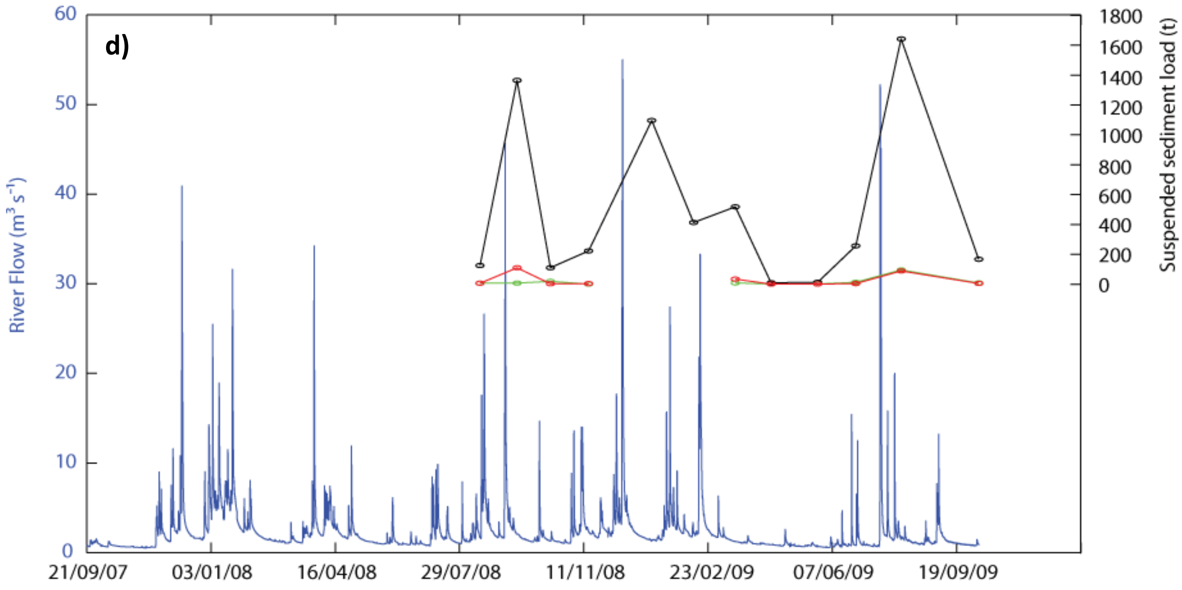


Figure A1: The estimated river discharge plotted alongside reference load estimates (black line), TIMs A measurements (green line) and TIMs B measurements (red line) at: **a)** Esk at Danby; **b)** Glaisdale Beck; **c)** Esk at Grosmont and; **d)** Rye at Broadway Foot.

Figure A1 (a – d) clearly indicates a large number of high flow events, which are flashy in nature. At a qualitative level, the reference sediment load for each of the catchments appears to show some synchronicity with the estimated discharge. Periods of sustained low flow e.g. February – June 2009 produce negligible suspended sediment loads, whereas periods containing individual or multiple moderate to high flow events consistently produce the greatest sediment loadings. Additionally, the peaks in the TIMs load estimates show a degree of synchronicity to the reference sediment loads albeit the TIMs loads are considerably smaller with a much more dampened response.

Looking in more detail at the comparability between the reference and TIMs load estimates, the degree of underestimation in the TIMs estimates is clear. Over the duration of the entire monitoring period, the TIMs loads underestimate the reference load by between

96.31% and 66.38% (Table A1). This level of underestimation indicates that the TIMs are clearly an unacceptable means of quantifying the absolute fluvial fine suspended sediment loads. The incomparability between the TIMs and reference loadings is exemplified by calculation of the Nash Sutcliffe coefficients (see Table A1.). For each of the sites, this coefficient is below zero, ranging from between -0.444 and -0.9783. This highlights deviations from the 1:1 line and confirms that the method is not an efficient indicator of total suspended sediment load.

	Reference Load (t)	TIMs Load (as % of reference load)	Nash-Sutcliffe Coefficient
Danby A	10101	5.40	-0.9783
Danby B	10101	6.35	-0.8513
Glaisdale A	806	33.62	-0.6950
Glaisdale B	578*	13.94	-0.4850
Grosmont	18667	6.66	-0.4861
Broadway Foot A	4429	3.69	-0.5308
Broadway Foot B	4429	5.77	-0.4444

Table A1: A comparison between the reference and TIMs derived sediment loads alongside the Nash-Sutcliffe coefficient. * Where the reference load varies between the two sites this is due to the TIMs becoming dislodged and lost to the river, resulting in missing period(s) in the sampling.

A3.2 Relative Efficiency of the TIMs

Although it has been ascertained in the previous section that the TIMs are not able to predict the actual suspended sediment load, there may be potential for their use in characterising the patterns of suspended sediment transfer in fluvial systems providing that the sampler is precise and underestimates the sediment load in a predictable and consistent manner throughout the duration of a monitoring campaign. Additionally, it is important that the device is capable of gathering sediment flux data which is comparable at multiple points in the river cross-section i.e. multiple samplers must provide comparable fine suspended sediment load estimates. This latter point can also be expanded to incorporate the ability of multiple samplers to capture fine sediment with comparable physical properties (i.e. particle size, organic and carbonate content, magnetic susceptibility). These prerequisites were assessed in three main ways:

1) Regression analysis of the relationship between the reference flux and TIMs flux estimates.
2) The coefficients of the regression equations between reference sediment load and TIMs A/TIMs B were compared.
3) ANOVA analysis of the sediment properties collected by TIMs A and B.

Results of regression analysis between the reference and TIMs sediment loads are shown in Figure A2 (a – d). The significance level of the relationship is also shown. Of note is that four of the seven relations are statistically significant at the 99% level, with two instances where the relationship is significant at the 95% level. Only one relation is not significant at the 95% level.

The regression relationships between the reference sediment load and TIMs A/TIMs B at Broadway Foot are statistically significant at the 95% and 99% levels respectively. The slope coefficients of the regression are 3.5% and 6.7% respectively, which are statistically similar (Table A2). The origins are proximal to zero, yet not statistically similar. Despite the comparable behaviour of the TIMs samplers, there is clearly some inherent sampling bias between the samplers. Most notably, between 11th February and 18th March 2009 the reference sediment load is 1364 t however, TIMs A estimates a load of 29 t whilst TIMs B estimates a load of 114 t. This reduces the slope coefficient for sampler A. Given the dramatic underestimation of sampler A during this period it is feasible that the sampler became obstructed by debris resulting in a blockage of the sampler intake. This is one of the limitations with using the sampler which cannot be predicted nor quantified (McDonald et al., 2010).

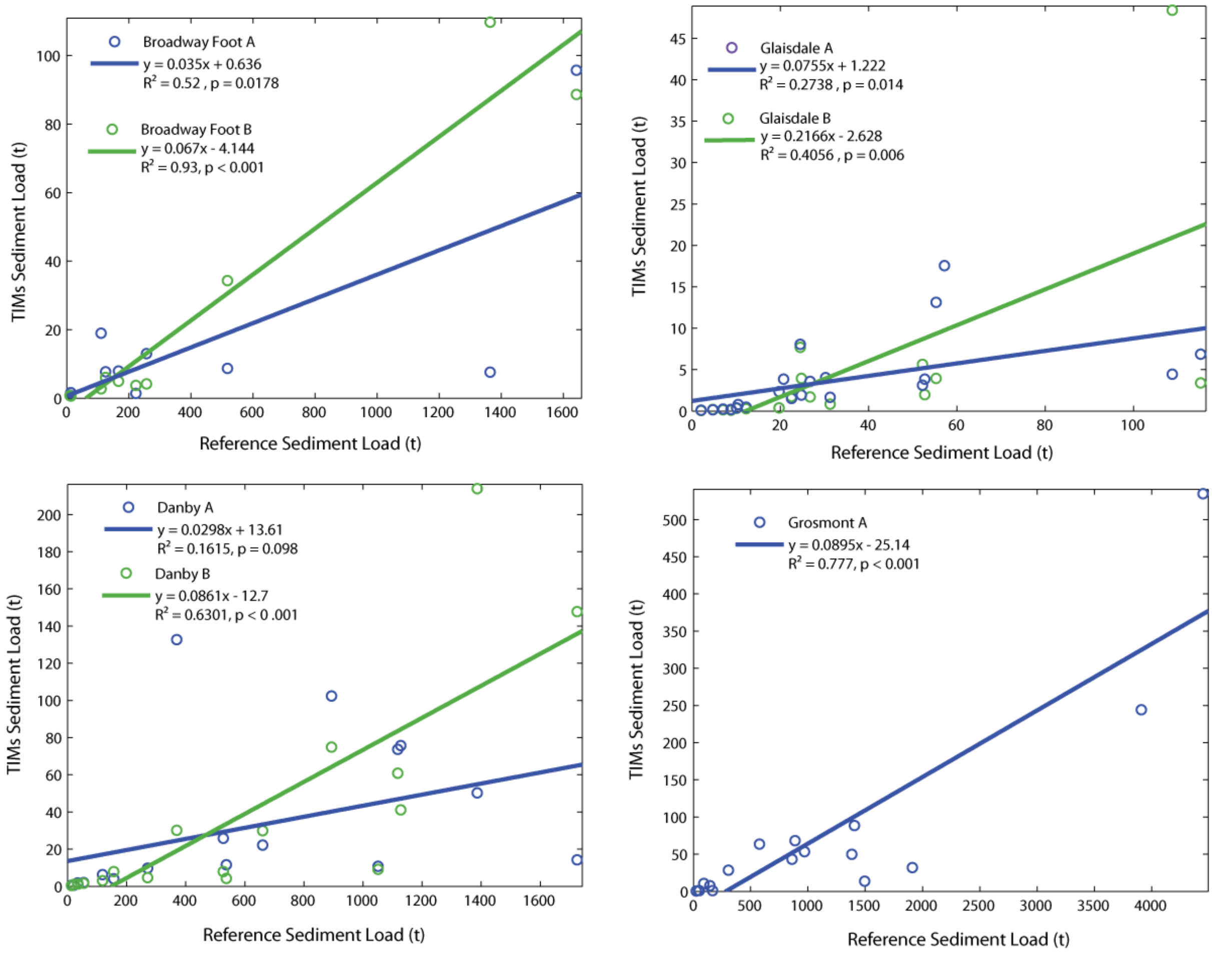


Figure A2: Linear regression by least squares for the relationship between the reference and TIMs derived sediment loads at: **a)** Rye at Broadway Foot; **b)** Glaisdale Beck; **c)** Esk at Danby and; **d)** Esk at Grosmont.

Both of the regression fits between reference sediment load and TIMs A/TIMs B at Glaisdale are statistically significant at the 95% and 99% levels respectively. The slope coefficients are 7.6% and 21.7% respectively which are statistically similar. The origins are once more proximal to zero, yet not statistically similar. In this analysis, one point is omitted from the analysis. Between 30th August 2008 and 28th September 2008, the estimated load from TIMs A is 193 t. However, the reference load is only 109 t. On this occasion there appears to have been some preferential sampling by sampler A. This is perhaps a result of channel flow being routed towards the sampler by debris trapped within the channel. This is the only occasion where the efficiency of the TIMs exceeds 100% and it is therefore omitted from analysis.

At the Danby monitoring site the linear fit between reference sediment load and TIMs A is poor (R^2 = 0.16) and is not statistically significant at the 95% level, whereas sampler B is highly significant (R^2 = 0.63). The estimated slope for TIMs B is 8.6%. This is similar to the slope coefficients of other samplers which produce sediment load estimates statistically similar to reference levels. At Grosmont, only one sampler was installed so therefore analysis is limited to assessing the efficiency of the sampler with reference to the reference load. In this case, the relationship is significant at the 99.9% level, with an R^2 of 0.78. The slope at this site is 8.9%.

	Intercept (T and *p* values)		Slope (T and *P* values)	
Broadway Foot A vs B	0.5	0.62	-2.34	*0.03*
Danby A vs B	1.45	0.16	2.38	*0.02*
Glaisdale A vs B	1.2	0.24	-2.03	*0.05*

Table A2: Results of t-tests on intercept and slope coefficients for each of the monitoring stations. Statistically significant relationships are italicised.

Given that the TIMs has been highlighted as having potential for being able to assess the relative changes in suspended sediment flux, the consistency of additional physical properties are assessed by comparing measurements between two samplers in the same cross-section of flow. The determinants tested for differences are sediment mass, median absolute particle size, magnetic susceptibility, organic and carbonate content. At each of the monitoring locations and for all the parameters tested apart from magnetic susceptibility at Danby, the results of the Mann–Whitney U test shows there are no statistically significant differences ($P > 0.05$) suggesting that the median values measured over the entire monitoring period are indeed similar. This provides us with confidence that the sampler is consistent and precise in these environments. The summary statistics and results of the Mann–Whitney U test are provided in Table A3. Although all parameters are statistically similar, it is clear that the sediment quality indicators (i.e. magnetic susceptibility, organic and carbonate content) are most stable between samplers, whereas the median absolute deviation for sediment mass and median grain size are more varied. These findings are entirely expected and could be hypothesised due to the mass and particle size of the recovered material being affected by both in-channel hydraulics, sampler positioning and the sediment source, whereas the sediment quality descriptors may be affected to a lesser extent, with properties being relatively stable through the cross-section with a lesser impact of flow hydraulics.

	Danby A [CV(%)]	Danby B [CV(%)]	Total DF	F	*P* - value
Mass Recovered (g)	66.12 [85.43]	63.95 [90.41]	43	0.02	0.9005
Median Absolute Particle Size (µm)	36.55 [117.67]	36.39 [174.31]	33	0.03	0.8580
X_{lf} (10^{-6} m^3 kg^{-1})	0.18 [23.39]	0.20 [17.11]	19	1.64	0.2166
Organic Content (%)	10.08 [37.04]	11.15 [30.58]	39	0.9	0.3486
Carbonate Content (%)	1.08 [44.56]	1.12 [36.20]	21	0.07	0.7996

	Glaisdale A	Glaisdale B	Total DF	F	*P* - value
Mass Recovered (g)	69.43 [120.00]	39.67 [89.53]	35	1.94	0.1724
Median Absolute Particle Size (µm)	18.44 [96.56]	25.95 [199.14]	33	0.32	0.5751
X_{lf} (10^{-6} m^3 kg^{-1})	0.18 [14.75]	0.16 [17.68]	15	0.88	0.3646
Organic Content (%)	10.51 [28.48]	10.43 [36.01]	31	0	0.9465
Carbonate Content (%)	1.24 [30.44]	1.60 [20.42]	19	0.02	0.8782

	Broadway Foot A	Broadway Foot B	Total DF	F	*p* - value
Mass Recovered (g)	35.33 [98.79]	62.85 [159.29]	19	0.67	0.4224
Median Absolute Particle Size (µm)	26.03 [75.65]	69.69 [120.22]	17	2.32	0.1476
X_{lf} (10^{-6} m^3 kg^{-1})	0.16 [24.64]	0.17 [36.87]	13	0.02	0.8881
Organic Content (%)	14.27 [36.16]	17.62 [77.82]	15	0.42	0.5287
Carbonate Content (%)	1.19 [38.80]	1.05 [31.36]	15	0.48	0.4981

Table A3: Average monthly values, coefficients of variation [CV(%)] of sediment properties along with results of one-way ANOVA are provided.

A4 Section Summary

Time integrated Mass-flux samplers were deployed in two adjacent catchments in the North York Moors National Park in North Yorkshire, UK in order to assess the extent to which the samplers were able to estimate the suspended sediment load over the course of a 2 year monitoring period. Having shown that the TIMs significantly underestimated the actual (or reference) sediment load, their relative efficiency was assessed. It was determined that in 6 out of the 7 cases a statistically strong ($P < 0.05$) relation between the reference and TIMs loads was observed. This showed that the TIMs operate consistently over prolonged periods, underestimating the actual sediment load in a predictable manner. At the locations where multiple samplers were installed, the coefficients of determination for the aforementioned regression were tested for similarities. In each case the TIMs slope coefficients were statistically similar ($P < 0.05$). Finally the measurements of a range of physical fine sediment properties were compared at the sites where multiple samplers were located. At all locations and for all the parameters, the differences between the measurements were statistically similar. However, further investigations under field conditions are required to assess the relationship between the ambient and sampler intake velocity in order to determine whether the sampler is in fact operating flow proportionally.

Annex B: Assessment of the coulter granulometer

Given that no recent tests of the operational efficacy of the Coulter LS Series Granulometer had been undertaken, it was deemed necessary to analyse the PSD output using samples of know PSD's so that the measurements from the analytical apparatus could be interpreted with confidence. Three control samples were used for this test, covering the complete spectrum of possible particle sizes, from clay to coarse sands.

The settings of the coulter granulometer during the test runs were consistent with those used for the analysis of the sediments with the exception of the sonicator settings. This was turned off as this was deemed to be unnecessary due to the unconsolidated nature of the powder material in use. Prior to the sample run, detectors were aligned; offsets were measured, as was the background, for 60 seconds. Upon completion of the setup cycle, the control samples were added into the vessel where mixing of the samples was achieved using a constant pump speed of 75%. Total obscuration of the lens following the addition of the control samples was consistent with the required 10% ± 3%. The main cycle was then run for 90 seconds to produce the observed data.

The first reference material used was a unimodal medium silt based material with an arithmetic mean value of 15.14 ± 1.8µm and a standard deviation of 7.19 ± 2.25µm. The response of the coulter granulometer to the addition of this sample is shown in Figure B1 Clearly, a unimodal distribution is observable with a modal value of 18.02µm, a median of 14.86µm and a mean value of 14.09µm with a standard deviation of 7.043. This is extremely close to the actual value of the standard material. One can therefore be confident that the results produced by the coulter granulometer for silt dominated materials are accurate.

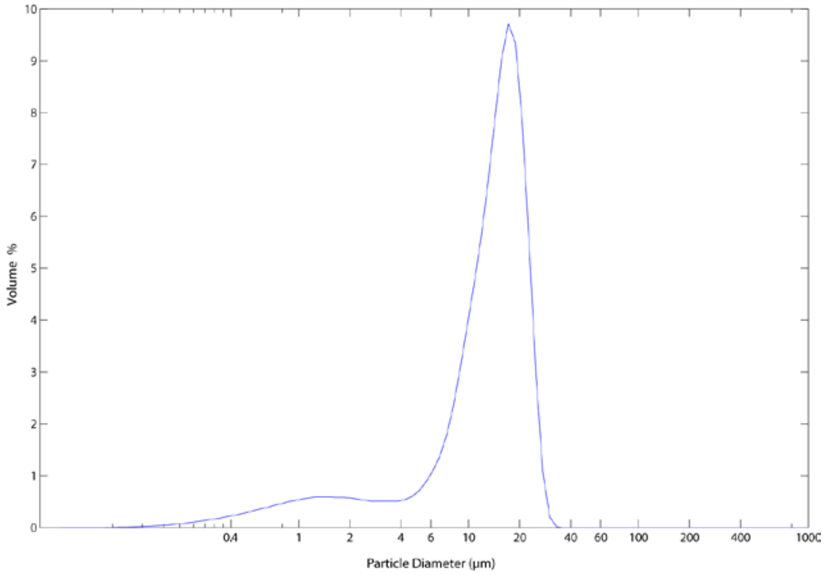


Figure B1: Output from the Coulter Granulometer following the input of medium silt sized reference material.

Following the successful run of the first reference material, the vessel was flushed and rinsed with deionised water until all of the reference material had been evacuated from the chamber (as indicated by a PIDS ratio of ~1.00). The set up cycle was once again completed and the second reference material could then be added. This reference material was a fine, unconsolidated, clay sized material with a uni-modal distribution and mean diameter of 0.296 ± 0.013µm. The standard deviation was 0.042 ± 0.010µm. The d_{10}, d_{50} and d_{90} of this material were 0.243 ± 0.024µm, 0.294 ± 0.018µm and 0.354 ± 0.035µm respectively. The response of the coulter granulometer to the addition of this sample is shown in Figure B2 Due to the poor agreement between the observed and reference material after the first run, two additional runs were carried out. As predicted, the output signal is dominated by clay sized material, which accounts for 79.8%, 89.2% and 91.7% of the sample volume for samples one to three respectively. The modal values of 0.298µm for all three runs is also comparable with that of the reference material (0.294 ± 0.018µm), as are the d_{10} and d_{50} with values of 0.244 and 0.290µm (average of three runs). However, contrary to what would be expected; a second, weaker signal is observable from the data output. This is between 52.63 and 213µm and accounts for 20.2%, 10.8% and 8.3% of the sample volume for each of the runs, which creates an elevated d_{90} value of 77.940 (average of three runs). This signal causes the mean values to become elevated to 25.67, 16.92 and 13.33µm with standard deviations of 52.46, 48.64 and 44.11µm for each of the three runs respectively. Although these values are not significantly different from the reference materials (at the 95% level), it appears there may be appreciable bias towards the coarse fraction, possibly caused by numerous very fine particles being viewed as large, singular entities. This issue could be further exacerbated by the process of aggregation within the chamber which is common with natural sediment. Despite these issues, the broad characteristics of the material may still be accurately described by the coulter granulometer.

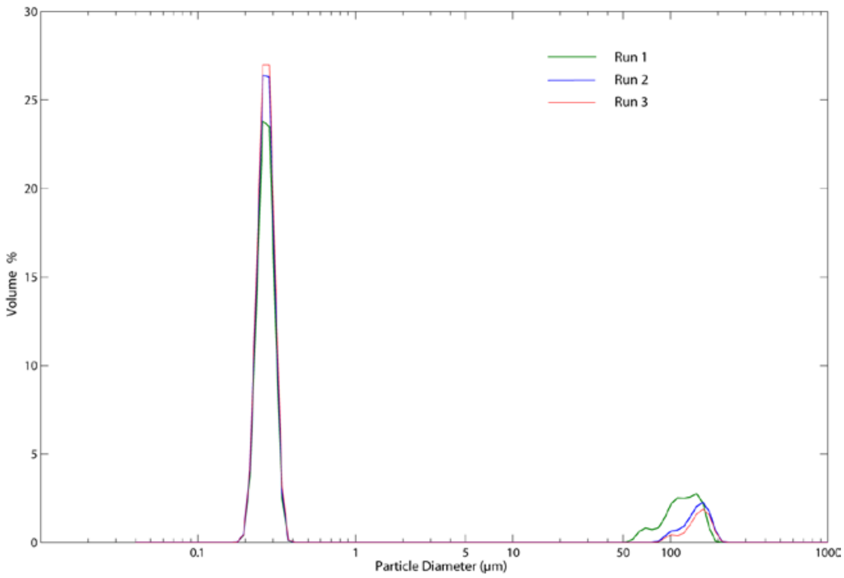


Figure B2: Output from the Coulter Granulometer following the input of clay sized reference material.

Following the completion of validation tests using the second standard material, the vessel and coulter system was once more flushed with deionised water, using the same method / criteria as described previously. Following this, the chamber was ready for the addition of the final reference material. This consisted of sand sized particles with a mean value of 568 ± 34.5µm and a standard deviation of 50.4 ± 22.5µm. The sample has a unimodal distribution with a d_{10}, d_{50} and d_{90} of 502 ± 25.10µm, 567 ± 17.01 and 640 ± 32.00µm respectively. As can be seen in Figure 4.13, analysis of the sample material by the coulter granulometer produced an arithmetic mean value of 570.6 ± 36.60µm, d_{10}, d_{50} and d_{90} values of 514.3µm, 568.8µm and 628.8µm respectively. Clearly, these are in very close agreement with the actual reference material values, indicating that the coulter granulometer is capable of correctly assessing the characteristics of coarse, sand sized materials.

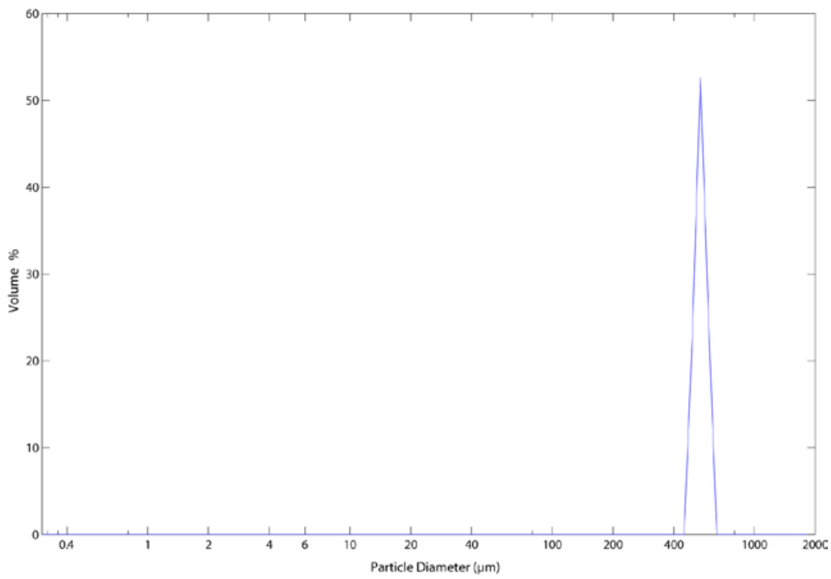


Figure B3: Output from the Coulter Granulometer following the input of sand sized reference material.

References

Abtew, W. & Powell, B. (2004). Water quality sampling schemes for variable flow canals at remote sites. *JAWRA Journal of the American Water Resources Association,* **40,** 1197-1204.

Achite, M. & Ouillon, S. (2007). *Suspended sediment transport in a semiarid watershed, wadi abd, algeria (1973-1995),* Kidlington, ROYAUME-UNI, Elsevier.

Alexandrov, Y., Laronne, J. B. & Reid, I. (2007). Intra-event and inter-seasonal behaviour of suspended sediment in flash floods of the semi-arid northern negev, israel. *Geomorphology,* **85,** 85-97.

American Society for Testing and Materials (Astm) 2000. Standard test methods for determining sediment concentration in water samples: D 3977-97.

Ampontuah, E. O., Robinson, J. S. & Nortcliff, S. (2006). Assessment of soil particle redistribution on two contrasting cultivated hillslopes. *Geoderma,* **132,** 324-343.

Anderson, C. W. 2004. Turbidity. U.S.D.I. Geological survey techniques of water-resources investigations.

Ankcorn, P. D. (Year). Clarifying turbidity - the potential and limitations of turbidity as a surrogate for water-quality monitoring. *In:* Georgia Water Resources Conference, 23 - 24 April 2003 Athens, Georgia.

Ankers, C., Walling, D. E. & Smith, R. P. (2003). The influence of catchment characteristics on suspended sediment properties. *Hydrobiologia,* **494,** 159-167.

Annandale, G. W. (1990). Discussion of ``uncertainty in suspended sediment transport curves'' by edward a. Mcbean and sabah al-nassri (january, 1988, vol. 114, no. 1). *Journal of Hydraulic Engineering,* **116,** 140-141.

Arnborg, L., Walker, H. J. & Peippo, J. (1967). Suspended load in the colville river, alaska, 1962. *Geografiska Annaler. Series A, Physical Geography,* **49,** 131-144.

Arnold-Forster 2002. Benefits to environment and economy through eu structural funds, with special reference to the north york moors national park. *In:* Burt, T. P., Thompson, D. B. A. & Warburton, J. (eds.) *The British Uplands: Dynamics of Change.* JNCC.

Asselman, N. E. M. (1999). Suspended sediment dynamics in a large drainage basin: The river rhine. *Hydrological Processes,* **13,** 1437-1450.

Asselman, N. E. M. (2000). Fitting and interpretation of sediment rating curves. *Journal of Hydrology,* **234,** 228 - 248.

Bača, P. (2008). Hysteresis effect in suspended sediment concentration in the rybárik basin, slovakia. *Hydrological Sciences,* **53,** 224 - 235.

Ball, D. F. (1964). Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Journal of Soil Science,* **15,** 84-92.

Ball, J. 1939. Contributions to the geography of egypt. Cairo: Government Press.

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., Newbold, J. D. & Sabater, F. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geosci,* **1,** 95-100.

Beasley, C. R. & Roberts, D. (1999). Towards a strategy for the conservation of the freshwater pearl mussel margaritifera margaritifera in county donegal, ireland. *Biological Conservation,* **89,** 275-284.

Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M. & Kirk, G. J. D. (2005). Carbon losses from all soils across england and wales 1978-2003. *Nature,* **437,** 245-248.

Benkhaled, A. & Remini , B. (2003). Analysis of a sediment rating curve in wahrane river basin (algeria). *Revue des sciences de l'eau,* **16,** 333 - 356.

Bent, G. C., Gray, J. R., Smith, K. P. & Glysson, G. D. 2001. A synopsis of technical issues for monitoring sediment in highway and urban runoff. *US Geological society open-file report.* Reston, VA: USA.
Berke, B. & Rakoczi, L. (Year). Latest achievements in the development of nuclear suspended sediment gauges. *In:* Proceedings of the Florence Symposium, 1981 Florence, Italy. IAHS.
Beven, K. J. & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Science Bulletins,* **24,** 43 - 69.
Bilby, R. E. (1981). Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology,* **62,** 1234 - 1243.
Bilotta, G. S. & Brazier, R. E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research,* **42,** 2849-2861.
Bilotta, G. S., Krueger, T., Brazier, R. E., Butler, P., Freer, J., Hawkins, J. M. B., Haygarth, P. M., Macleod, C. J. A. & Quinton, J. N. (2010). Assessing catchment-scale erosion and yields of suspended solids from improved temperate grassland. *Journal of Environmental Monitoring,* **12,** 731-739.
Birkinshaw, S. J. & Bathurst, J. C. (2006). Model study of the relationship between sediment yield and river basin area. *Earth Surface Processes and Landforms,* **31,** 750 - 761.
Bishop, K., Buffam, I., Erlandsson, M., Fölster , J., Laudon, H., Seibert, J. & Temnerud, J. (2008). Aqua incognita: The unknown headwaters. *Hydrological Processes*.
Black, K. P. & Rosenberg, M. A. (1994). Suspended sand measurements in a turbulent environment: Field comparison of optical and pump sampling techniques. *Coastal Engineering,* **24,** 137-150.
Blum, W. & Eswaran, H. (2004). Editorial: Soils and sediments in the anthropocene. *Journal of Soils and Sediments,* **4,** 71-71.
Bogen, J. (1980). The hysteresis effect of sediment transport (river) systems. *Norsk Geografisk Tidsskrift* **34,** 45 - 54.
Bogen, J. (Year). Monitoring grain size of suspended sediments in rivers. *In:* Erosion and Sediment Transport Monitoring Programmes in River Basins 1992 Proceedings of the Oslo Symposium, August 1992. IAHS, 183 - 190.
Bolland, J. D., Bracken, L. J., Martin, R. & Lucas, M. C. (2010). A protocol for stocking hatchery reared freshwater pearl mussel margaritifera margaritifera. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **20,** 695-704.
Bormann, F. H., Likens, G. E., Siccama, T. G., Pierce, R. S. & Eaton, J. S. (1974). The export of nutrients and recovery of stable conditions following deforestation at hubbard brook. *Ecological Monographs,* **44,** 255-277.
Bracken, L. & Warburton, J. 2005. Monitoring fine sediment transfer in the river esk, north york moors, northern england: Final report. Durham University.
Brandt, S. A. (2000). Classification of geomorphological effects downstream of dams. *Catena,* **40,** 375-401.
Braskerud, B. C. (2001). The influence of vegetation on sedimentation and resuspension of soil particles in small constructed wetlands. *Journal of Environmental Quality,* **30,** 1447-1457.
Brazier, R. (2004). Quantifying soil erosion by water in the uk: A review of monitoring and modelling approaches. *Progress in Physical Geography,* **28,** 340-365.
Brazier, R. E., Bilotta, G. S. & Haygarth, P. M. (2007). A perspective on the role of lowland, agricultural grasslands in contributing to erosion and water quality problems in the uk. *Earth Surface Processes and Landforms,* **32,** 964-967.
Brills, J. (2008). Sediment monitoring and the european water framework directive. *Ann Ist Super Sanita,* **44,** 218 - 223.

Brookes, A. (1987). River channel adjustments downstream from channelization works in england and wales. *Earth Surface Processes and Landforms,* **12,** 337-351.
Brookes, A. (1995a). Challenges and objectives for geomorphology in u.K. River management. *Earth Surface Processes and Landforms,* **20,** 593-610.
Brookes, A. (1995b). River channel restoration: Theory and practice. *In:* Gurnell, A. M. & Petts, G. E. (eds.) *Changing river channels.* Chichester: Wiley.
Brown, A. G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J.-J., Moldenhauer, K.-M. & Walling, D. E. (2009). From sedimentary records to sediment budgets: Multiple approaches to catchment sediment flux. *Geomorphology,* **108,** 35-47.
Burt, T. P. (2001). Integrated management of sensitive catchment systems. *Catena,* **42,** 275-290.
Burt, T. P., Donohoe, M. A. & Vann, A. R. (1983). The effect of forestry drainage operations on upland sediment yields: The results of a storm-based study. *Earth Surface Processes and Landforms,* **8,** 339-346.
Cambardella, C. A. & Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Sci. Soc. Am. J.,* **56,** 777-783.
Campell Scientific 1996. Pdcr1830 pressure transducer for depth measurement. Leicestershire, UK.
Caponera, D. A. (1992). *Principles of water law and administration; national and international.,* Rotterdam, Balkema.
Carling, P. A. (1983). Particulate dynamics, dissolved and total load, in two small basins, northern pennines, uk. *Hydrological Sciences,* **28,** 355 - 375.
Carling, P. A. (1984). Deposition of fine and coarse sand in an open-work gravel bed. *Canadian Journal of Fisheries and Aquatic Sciences,* **41,** 263 - 270.
Carroll, D. M. & Bendelow, V. C. (1981). *Soils of the north york moors,* Harpenden, Bartholomew Press.
Carvalho, L., Maberly, S., May, L., Reynolds, C., Hughes, M., Brazier, R., Heathwaite, L., Liu, S., Hilton, J., Bennion, H., Elliott, A., Willby, N., Dils, R., Phillips, G., Pope, L. & Fozzard, I. 2005. Risk assessment methodology for determining nutrient impacts in surface freshwater bodies. *Science Report SC020029/SR.*
Chanson, H., Takeuchi, M. & Trevethan, M. (2008). Using turbidity and acoustic backscatter intensity as surrogate measures of suspended sediment concentration in a small subtropical estuary. *Journal of Environmental Management,* **88,** 1406-1416.
Chaplot, V. & Poesen, J. (2012). Sediment, soil organic carbon and runoff delivery at various spatial scales. *Catena,* **88,** 46-56.
Cheng, N.-S. (1997). Simplified settling velocity formula for sediment particle. *Journal of Hydraulic Engineering,* **123,** 149-152.
Chesney, H. C. G. & Oliver, P. G. (1998). Conservation issues for margaritiferidae in the british isles and western europe. *Journal of Conchology,* **2,** 231 - 242.
Church, M. & Slaymaker, H. O. (1989). Disequilibrium of holocene sediment yield in glaciated british columbia. *Nature,* **337,** 452 - 454.
Colby, B. R. 1956. Relationship of sediment discharge to streamflow. Reston, VA: USA: US Geological Survey.
Collins, A. L. & Anthony, S. G. (2008a). Assessing the likelihood of catchments across england and wales meeting 'good ecological status' due to sediment contributions from agricultural sources. *Environmental Science & Policy,* **11,** 163-170.
Collins, A. L. & Anthony, S. G. (2008b). Predicting sediment inputs to aquatic ecosystems across england and wales under current environmental conditions. *Applied Geography,* **28,** 281-294.

Collins, A. L. & Mcgonigle, D. F. (2008). Monitoring and modelling diffuse pollution from agriculture for policy support: Uk and european experience. *Environmental Science & Policy,* **11,** 97-101.

Collins, A. L. & Walling, D. E. (1998). Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surface Processes and Landforms* **23,** 31 - 52.

Collins, A. L. & Walling, D. E. (2002). Selecting fingerprinting properties for discriminating potential suspended sediment sources in river basins. *Journal of Hydrology,* **261,** 218 - 244.

Collins, A. L. & Walling, D. E. (2004). Documenting catchment suspended sediment sources: Problems, approaches and prospects. *Progress in Physical Geography,* **28,** 159 - 196.

Collins, A. L., Walling, D. E. & Leeks, G. J. L. (1997a). Fingerprinting the origin of fluvial suspended sediment in larger river basins: Combining assessment of spatial provenance and source type. *Geografiska Annaler: Series A, Physical Geography,* **79,** 239-254.

Collins, A. L., Walling, D. E. & Leeks, G. J. L. (1997b). Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. *Catena,* **29,** 1 - 27.

Collins, A. L., Walling, D. E. & Leeks, G. J. L. (1998). Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surface Processes and Landforms,* **23,** 31 - 52.

Collins, A. L., Walling, D. E., Sichingabula, H. M. & Leeks, G. J. L. (2001). Suspended sediment source fingerprinting in a small tropical catchment and some management implications. *Applied Geography,* **21,** 387-412.

Cooper, D. M., Naden, P., Old, G. & Laize, C. 2008. Development of guideline sediment targets to support management of sediment inputs into aquatic systems. Sheffield: Natural England Research Report.

Córdova, J. R. & González, M. (1997). Sediment yield estimation in small watersheds based on streamflow and suspended sediment discharge measurements. *Soil Technology,* **11,** 57-65.

Cowan, W. L. (1956). Estimating hydraulic roughness coefficients. *Agricultural Engineering,* **37,** 473 - 475.

Cox, N. J., Warburton, J., Armstrong, A. & Holiday, V. J. (2008). Fitting concentration and load rating curves with generalized linear models. *Earth Surface Processes and Landforms* **33,** 25 - 39.

Crisp, D. T. (1966). Input and output of minerals for an area of pennine moorland: The importance of precipitation, drainage, peat erosion and animals. *Journal of Applied Ecology,* **3,** 327-348.

Crisp, D. T. & Robson, S. (1979). Some effects of discharge upon the transport of animals and peat in a north pennine headstream. *Journal of Applied Ecology,* **38,** 1101 - 1105.

Crowe, S., Evans, M. G. & Allott, T. E. H. (2008). Geomorphological controls on the re-vegetation of erosion gullies in blanket peat: Implications for bog restoration. *Mires and Peat,* **1,** 1 - 14.

Cuffney, T. F. & Wallace, J. B. (1988). Particulate organic matter export from three headwater streams: Discrete versus continuous measurements. *Canadian Journal of Fisheries and Aquatic Sciences,* **45,** 2010-2016.

Cummins, K. W. (1973). Trophic relations of aquatic insects. *Annual Review of Entomology,* **18,** 183-206.

D & a Instrument Company. (2010). *Obs-3a information sheet* [Online]. Available: http://www.d-a-instruments.com/pdf/OBS3A.pdf [Accessed 13/07/2010].

Davide, V., Pardos, M., Diserens, J., Ugazio, G., Thomas, R. & Dominik, J. (2003). Characterisation of bed sediments and suspension of the river po (italy) during normal and high flow conditions. *Water Research,* **37,** 2847-2864.

Davies-Colley, R. J. & Smith, D. G. (2001). Turbidity, suspended sediment, and water clarity: A review. *Journal of the American Water Resources Association,* **37,** 1085 - 1101.

Davison, P. S., Withers, P. J. A., Lord, E. I., Betson, M. J. & Strömqvist, J. (2008). Psychic – a process-based model of phosphorus and sediment mobilisation and delivery within agricultural catchments. Part 1: Model description and parameterisation. *Journal of Hydrology,* **350,** 290-302.

Dawson, J. J. C. & Smith, P. (2007). Carbon losses from soil and its consequences for land-use management. *Science of The Total Environment,* **382,** 165-190.

De Vente, J. & Poesen, J. (2005). Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. *Earth-Science Reviews,* **71,** 95 - 125.

De Vente, J., Poesen, J., Arabkhedri, M. & Verstraeten, G. (2007). The sediment delivery problem revisited. *Progress in Physical Geography,* **31,** 155 - 178.

De Vente, J., Verduyn, R., Verstraeten, G., Vanmaercke, M. & Poesen, J. (2011). Factors controlling sediment yield at the catchment scale in nw mediterranean geoecosystems. *Journal of Soils and Sediments,* **11,** 690-707.

De Vos, J. A. (2001). Monitoring nitrate leaching from submerged drains. *Journal of Environmental Quality,* **30,** 1092-1096.

Dean, W. E. J. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. *Journal of Sed. Petrol.,* **44,** 242 - 248.

Dedkov, A. (2004). The relationship between sediment yield and drainage basin area. *In:* Golosov, V. N., Belyaev, V. R. & Waling, D. E. (eds.) *Sediment transfer through the fluvial system, iahs publication no. 228.* Wallingford: IAHS Press.

Dedkov, A. P. & Mozzherin, V. I. (1984). Erosia i stok nanosov na zemle (erosion and sediment yield on the earth) (in russian with an english summary). *Izdatelstvo Kazanskogo Universiteta*.

Defra. (2004). *Freshwater quality* [Online]. Available: http://www.defra.gov.uk/evidence/statistics/environment/inlwater/iwhmsdb.htm [Accessed 27/07/2010].

Dekkers, M. J. (1997). Environmental magnetism: An introduction. *Geologie en Mijnbouw,* **76,** 163-182.

Dickinson, W. T. (Year). Accuracy and precision of suspended sediment loads. *In:* Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). 1981. IAHS Publications, 195 - 202.

Dixon, W. & Chiswell, B. (1996). Review of aquatic monitoring program design. *Water Research,* **30,** 1935-1948.

Doty, C. W. & Carter, C. E. (1965). Rates and particle-size distribution of soil erosion from unit source areas. *ransactions of the American Society of Agricultural Engineers,* **8,** 309 - 311.

Droppo, I. G. (2001). Rethinking what constitutes suspended sediment. *Hydrological Processes,* **15,** 1551 - 1564.

Duan, N. (1983). Smearing estimate: A nonparametric retransformation method. *Journal of the American Statistical Association,* **78,** 605-610.

Dunne, T. & Leopold, L. B. 1978. Water in environmental planning: San francisco.

Duvert, C., Gratiot, N., Evrard, O., Navratil, O., Némery, J., Prat, C. & Esteves, M. (2010). Drivers of erosion and suspended sediment transport in three headwater catchments of the mexican central highlands. *Geomorphology,* **123,** 243-256.

Eaton, B. C., Moore, R. D. & Giles, T. R. (2010). Forest fire, bank strength and channel instability: The 'unusual' response of fishtrap creek, british columbia. *Earth Surface Processes and Landforms,* **35,** 1167-1183.
Eder, A., Strauss, P., Krueger, T. & Quinton, J. N. (2010). Comparative calculation of suspended sediment loads with respect to hysteresis effects (in the petzenkirchen catchment, austria). *Journal of Hydrology,* **389,** 168-176.
Egglinshaw, H. J. & Shackley, P. E. (1971). Suspended organic matter in fast-flowing streams in scotland. *Freshwater Biology,* **1,** 273 - 285.
Environment Agency 2006. Esk and coastal streams catchment flood management plans - scoping report, september 2006.
Environment Agency 2007. Yorkshire derwent catchment flood management plan. *Managing Flood Risk.*
Environment Agency. (1998). *River habitat quality: The physical character of rivers and stream in the uk and isle of man,* Bristol, Environment Agency.
Etchells, T., Tan, K. S. & Fox, D. (Year). Quantifying the uncertainty of nutrient load estimates in the shepparton irrigation region. *In:* Proceedings MODSIM05 International Congress on Modelling and Simulation, Advances and Applications for Management and Decision Making, 2005.
Eu Water Directors 2005. Common implementation stratergy for the water framework directive: Environmental objectives under the water framework directive - policy summary and background document.
Evans, C., Norris, D. & Rowe, E. 2005. A regional water and soil quality survey of the north york moors. *Critical Loads and Dynamic Modelling Optional activity B: Report to the Department of the Environment, Food and Rural Affairs under Contract No. CPEA 19.* Centre for Ecology and Hydrology.
Evans, D. J. & Gibson, C. E. (2006). *Sediment in the river bush, northern ireland,* Wallingford, UK, CABI Publishing.
Evans, D. J., Gibson, C. E. & Rossell, R. S. (2006a). Sediment loads and sources in heavily modified irish catchments: A move towards informed management strategies. *Geomorphology,* **79,** 93-113.
Evans, M. & Warburton, J. (2005). Sediment budget for an eroding peat-moorland catchment in northern england. *Earth Surface Processes and Landforms,* **30,** 557-577.
Evans, M., Warburton, J. & Yang, J. (2006b). Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. *Geomorphology,* **79,** 45-57.
Evans, R. (1993). Sensitivity of the british landscape to erosion. *In:* Thomas, D. S. G. & Allison, R. J. (eds.) *Landscape sensitivity.* Chichester: Wiley.
Evans, R. (1997). Accelerated soil erosion in britain. *Geography,* **82,** 149 - 162.
Evans, R. (2006). Land use, sediment delivery and sediment yield in england and wales. *In:* Owens, P. N. & Collins, A. J. (eds.) *Soil erosion and sediment redistribution in river channels.* Wallingford, UK: CAB International.
Fargas, D., Casasnovas, J. A. M. & Poch, R. (1997). Identification of critical sediment source areas at regional level. *Physics and Chemistry of The Earth,* **22,** 355-359.
Fenn, C. R., Gurnell, A. M. & Beecroft, I. R. (1985). An evaluation of the use of suspended sediment rating curves for the prediction of suspended sediment concentration in a proglacial stream. *Geografiska Annaler. Series A, Physical Geography,* **67,** 71-82.
Ferguson, R. I. (1986). River loads underestimated by rating curves. *Water Resources Research,* **22,** 74 - 76.
Ferguson, R. I. (1987). Accuracy and precision of methods for estimating river loads. *Earth Surface Processes and Landforms,* **12,** 95-104.

Ferguson, R. I., Grieve, I. C. & Harrison, D. J. (1991). Disentangling land use effects on sediment yield from year to year climatic variation. *In:* Peters, N. E. & Walling, D. E. (eds.) *Sediment and stream water quality in a changing environment: Trends and explanation. Proceedings of the vienna symposium.* Wallingford: IAHS Press.

Ferguson, R. I. & Stott, T. A. (1987). Forestry effects on suspended sediment and bedload yields in the balquhidder catchments, central scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh,* **78,** 379-384.

Fielding, F. G. A. & Haworth, P. F. (1999). *Upland habitats,* London, Routledge.

Foltz, R. B., Yanosek, K. A. & Brown, T. M. (2008). Sediment concentration and turbidity changes during culvert removals. *Journal of Environmental Management,* **87,** 329-340.

Fox, J. F. & Papanicolaou, A. N. (2007). The use of carbon and nitrogen isotopes to study watershed erosion processes. *Journal of the American Water Resources Association,* **43,** 1047-1064.

Francis, I. S. (1990). Blanket peat erosion in a mid-wales catchment during two drought years. *Earth Surface Processes and Landforms,* **15,** 445-456.

Francis, I. S. & Taylor, J. A. (1989). The effect of forestry drainage operations on upland sediment yields: A study of two peat-covered catchments. *Earth Surface Processes and Landforms,* **14,** 73-83.

Fryirs, K. (2012). (dis)connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*.

Fryirs, K. A., Brierley, G. J., Preston, N. J. & Kasai, M. (2007). Buffers, barriers and blankets : The (dis)connectivity of catchment-scale sediment cascades. *Catena,* **70,** 49 - 67.

Fugate, D. C. & Friedrichs, C. T. (2002). Determining concentration and fall velocity of estuarine particle populations using adv, obs and lisst. *Continental Shelf Research,* **22,** 1867-1886.

Fullen, M. A. (1992). Erosion rates on bare loamy soils in east shropshire, uk. *Soil Use and Management,* **8,** 157 - 162.

Gao, P. & Puckett, J. (2011). A new approach for linking event-based upland sediment sources to downstream suspended sediment transport. *Earth Surface Processes and Landforms***,** n/a-n/a.

Geist, J. (2005). *Conservation genetics and ecology of european freshwater pearl mussels (margaritifera margaritifera l.).* PhD, Universität München.

Geist, J. (2010). Strategies for the conservation of endangered freshwater pearl mussels (*margaritifera margaritifera* l.): A synthesis of conservation genetics and ecology *Hydrobiologia,* **644,** 69-88.

Geist, J. & Auerswald, K. (2007). Physiochemical stream bed characteristics and recruitment of the freshwater pearl mussel (*margaritifera margaritifera)*. *Freshwater Biology*.

Gimingham, C. H. 2002. Foreword: A vision for the uplands. *In:* Burt, T. P., Thompson, D. B. A. & Warburton, J. (eds.) *The British Uplands: Dynamics of change.* JNCC.

Gippel, C. J. (1989). The use of turbidimeters in suspended sediment research. *Hydrobiologia,* **176-177,** 465-480.

Gippel, C. J. (1995). Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes,* **9,** 83 - 97.

Gonzalez-Hidalgo, J. C., Batalla, R. J., Cerdà, A. & De Luis, M. (2010). Contribution of the largest events to suspended sediment transport across the USA. *Land Degradation & Development,* **21,** 83-91.

Gordon, J. G., Brazier, V., Haynes, V. M. & Grieve, I. C. 2002. Geomorphological heritage and sensitivity in the uplands: A case study from the cairngorm mountains, scotland. *In:* Burt, T. P., Thompson, D. B. A. & Warburton, J. (eds.) *The british uplands: dynamics of change.* DEFRA.

Gottschalk, L. C. (1945). Effects of soil erosion on navigation in upper chesapeake bay. *Geographical Review,* **35,** 219-238.
Graczyk, D. J., Robertson, D. M., Rose, W. J. & Steuer, J. J. 2000. Comparison of water-quality samples collected by siphon samplers and automatic samplers in wisconsin. Reston, VA: USA: United States Geological Survey.
Granata, T., Asce, M., Cheng, F. & Nechvatal, M. (2008). Discharge and suspended sediment transport during deconstruction of a low-head dam. *Journal of Hydraulic Engineering-Asce,* **134,** 652-657.
Granger, S. J., Bol, R., Butler, P. J., Haygarth, P. M., Naden, P., Old, G., Owens, P. N. & Smith, B. P. G. (2007). Processes affecting transfer of sediment and colloids, with associated phosphorus, from intensively farmed grasslands: Tracing sediment and organic matter. *Hydrological Processes,* **21,** 417-422.
Gray, J. R. & Gartner, J. W. (2009). Technological advances in suspended-sediment surrogate monitoring. *Water Resour. Res.,* **45,** W00D29.
Gray, J. R., Glysson, G. D. & Edwards, T. K. (2008). Suspended-sediment samplers and sampling methods. *In:* García, M. H. (ed.) *Sedimentation engineering: Processes, measurements, modeling, and practise.* Reston, Virginia: USA: ASCE Publications.
Gray, J. R., Glysson, G. D. & Mueller, D. S. 2002. Comparability and accuracy of fluvial seidment data - a view from the u.S. Geological survey. *Speciality Conference, Hydraulic Measurements and Experimental Methods.* Colorado, USA.
Gray, J. R. & Simões, F. J. M. (2008). Estimating sediment discharge. *In:* García, M. H. (ed.) *Sedimentation engineering: Processes, measurements, modeling and practise.* Reston, Virginia: UK: American Society of Civil Engineers.
Gray, J. S. (1999). Using science for better protection of the marine environment. *Marine Pollution Bulletin,* **39,** 3-10.
Gregory, K. J. & Walling, D. E. (1973). *Drainage basin form and process. A geomorphological approach,* London, Edward Arnold.
Grieve, I. C. (1984). Concentrations and annual loading of dissolved organic matter in a small moorland stream. *Freshwater Biology,* **14,** 533 - 537.
Grieve, I. C., Davidson, D. A. & Gordon, J. E. (1995). Nature, extent and severity of soil erosion in upland scotland. *Land Degradation & Development,* **6,** 41-55.
Guy, H. P. & Norman, V. W. 1970. Field methods for measurement of fluvial sediment, chapter c2. *US Geological Survey Techniques of Water Resources Investigations.*
Habitats Directive 1992. Council directive 92/43/eec of 21 may 1992 on the conservation of natural habitats and of wild fauna and flora, official journal of the european communities (21.05.1992).
Harris, R., Sullivan, K., Cafferata, P., Munn, J. & Faucher, K. (2007). Applications of turbidity monitoring to forest management in california. *Environmental Management,* **40,** 531-543.
Hart, A. (2001). Mann-whitney test is not just a test of medians: Differences in spread can be important. *BMJ,* **323,** 391-393.
Hastie, L. C., Boon, P. J. & Young, M. R. (2000). Physical microhabitat requirements of freshwater pearl mussels, margaritifera margaritifera (l.). *Hydrobiologia,* **429,** 59-71.
Hastie, L. C. & Young, M. R. (2001). Freshwater pearl mussel (*margaritifera margaritifera*) glochidiosis in wild and farmed salmonid stocks in scotland *Hydrobiologia,* **445,** 109-119.
Hatfield, R. G. & Maher, B. A. (2008). Suspended sediment characterization and tracing using a magnetic fingerprinting technique: Bassenthwaite lake, cumbria, uk. *The Holocene,* **18,** 105-115.

Hatfield, R. G. & Maher, B. A. (2009). Fingerprinting upland sediment sources: Particle size - specific magnetic linkages between soils, lake sediments and suspended sediments. *Earth Surface Processes and Landforms,* **34,** 1359-1373.

Haygarth, P. M., Bilotta, G. S., Bol, R., Brazier, R. E., Butler, P. J., Freer, J., Gimbert, L. J., Granger, S. J., Krueger, T., Macleod, C. J. A., Naden, P., Old, G., Quinton, J. N., Smith, B. & Worsfold, P. (2006). Processes affecting transfer of sediment and colloids, with associated phosphorus, from intensively farmed grasslands: An overview of key issues. *Hydrological Processes,* **20,** 4407-4413.

Haygarth, P. M., Condron, L. M., Heathwaite, A. L., Turner, B. L. & Harris, G. P. (2005). The phosphorus transfer continuum: Linking source to impact with an interdisciplinary and multi-scaled approach. *Science of The Total Environment,* **344,** 5-14.

Haynes, R. J. & Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems,* **51,** 123-137.

Heathwaite, A. L., Burt, T. P. & Trudgill, S. T. (1990). Land-use controls on sediment production in a lowland catchment, south-west england. *In:* Boardman, J., Foster, I. D. L. & Dearing, J. A. (eds.) *Soil erosion on agricultural land.* Chichester: John Wiley & Sons.

Hedges, J. I., Mayorga, E., Tsamakis, E., Mcclain, M. E., Aufdenkampe, A., Quay, P., Richey, J. E., Benner, R., Opsahl, S., Black, B., Pimentel, T., Quintanilla, J. & Maurice, L. (2000). Organic matter in bolivian tributaries of the amazon river: A comparison to the lower mainstream. *Limnology and Oceanography,* **45,** 1449-1466.

Heiri, O., Lotter, A. F. & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology,* **25,** 101-110.

Helsel, D. R. & Hirsch, R. M. (1992). *Statistical methods in water resources,* Amsterdam, Netherlands, Elsevier.

Hicks, D. M., Gomez, B. & Trustman, N. A. (2000). Erosion thresholds and suspended sediment yields, waipaoa river basin, new zealand. *Water Resources Research,* **36,** 1129 - 1142.

Hillier, S. (2001). Particulate composition and origin of suspended sediment in the r. Don, aberdeenshire, uk. *Science of The Total Environment,* **265,** 281-293.

Holden, J., Chapman, P. J. & Labadz, J. C. (2004). Artificial drainage of peatlands: Hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography,* **28,** 95-123.

Hope, D., Billett, M. F. & Cresser, M. S. (1994). A review of the export of carbon in river water: Fluxes and processes. *Environmental Pollution,* **84,** 301-324.

Hopkinson, C. S., Buffam, I., Hobbie, J., Vallino, J., Perdue, M., Eversmeyer, B., Prahl, F., Covert, J., Hodson, R., Moran, M. A., Smith, E., Baross, J., Crump, B., Findlay, S. & Foreman, K. (1998). Terrestrial inputs of organic matter to coastal ecosystems: An intercomparison of chemical characteristics and bioavailability. *Biogeochemistry,* **43,** 211-234.

Horowitz, A. J. (1991). *A primer on sediment trace element chemistry.,* Chelsea, MI, Lewis Publishers.

Horowitz, A. J. (1995). *The use of suspended sediment and associated trace elements in water quality studies,* Wallingford, International Association of Hydrological Sciences.

Horowitz, A. J. (2003). An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrological Processes,* **17,** 3387-3409.

Horowitz, A. J. (2008). Determining annual suspended sediment and sediment-associated trace element and nutrient fluxes. *Science of The Total Environment,* **400,** 315-343.
Horowitz, A. J., Elrick, K. A. & Smith, J. J. (2001). Estimating suspended sediment and trace element fluxes in large river basins: Methodological considerations as applied to the nasqan programme. *Hydrological Processes,* **15,** 1107-1132.
Horowitz, A. J., Rinella, A. R., Lamothe, P., Miller, T. L., Edwards, T. K., Roche, R. L. & Rickert, D. A. (1990). Variations in suspended sediment and associated trace element concentrations in selected riverine cross sections. *Environmental Science & Technology,* **24,** 1313 - 1320.
Horsburgh, J. S., Jones, A. S., Stevens, D. K., Tarboton, D. G. & Mesner, N. O. (2010). A sensor network for high frequency estimation of water quality constituent fluxes using surrogates. *Environ. Model. Softw.,* **25,** 1031-1044.
http://Weather.Westerdale.Info. (2011). *North york moors weather* [Online]. [Accessed 11/12/2011].
Imeson, A. C. (1971). Heather burning and soil erosion on the north yorkshire moors. *Journal of Applied Ecology,* **8,** 537-542.
International Organisation for Standardisation 1999. ISO 7027: Water quality - determination of turbidity. Geneva, Switzerland.
Ipcc 2007. Climate change 2007: Impacts, adaptation and vulnerability working group ii contribution to the intergovernmental panel on climate change fourth assessment report: Summary for policymakers.
Irvine, K., Boelens, R., Fitzsimmons, J., Kemp, A. & Johnston, P. 2002. Review of monitoring and research to meet the needs of the eu water framework directive (2000-ds-5-m1). *Environmental RTDI Programme 2000–2006.*
Jansson, M. B. (1988). A global survey of sediment yield. *Geografiska Annaler. Series A, Physical Geography,* **70,** 81-98.
Jncc. (2011). *1029 freshwater pearl mussel: Margaritifera margaritifera* [Online]. Available: http://jncc.defra.gov.uk/protectedsites/sacselection/species.asp?FeatureIntCode=S1029 [Accessed 17/12/2011].
Joaquim, R. (2003). The freshwater pearl mussel [margaritifera margaritifera (l.)] (bivalvia, unionoida) rediscovered in portugal and threats to its survival. *Biological Conservation,* **114,** 447-452.
Johnson, R. C. (1993). Effects of forestry on suspended solids and bedload yields in the balquhidder catchments. *Journal of Hydrology,* **145,** 403-417.
Joint Nature Conservation Committee 2006. Ramsar information sheet: Uk11037: Lower derwent valley. *Information on RAMSAR Wetlands.*
Kao, S. J., Lee, T. Y. & Milliman, J. D. (2005). Calculating highly fluctuated suspended sediment fluxes from mountainous rivers in taiwan. *Terrestrial, Oceanic and Atmospheric Sciences Journal,* **16,** 653 - 657.
Keesstra, S. D., Van Dam, O., Verstraeten, G. & Van Huissteden, J. (2009). Changing sediment dynamics due to natural reforestation in the dragonja catchment, sw slovenia. *CATENA,* **78,** 60-71.
Kenney, B. C. (1982). Beware of spurious self-correlations! *Water Resources Research,* **18,** 1041 - 1048.
Khullar, N. K., Kothyari, U. C. & Raju, K. G. R. (2010). Suspended wash load transport of nonuniform sediments. *Journal of Hydraulic Engineering,* **136,** 534-543.
Kineke, G. C. & Sternberg, R. W. (1992). Measurements of high concentration suspended sediments using the optical backscatterance sensor. *Marine Geology,* **108,** 253-258.
Kirby, C., Newson, M. D. & Gliman, K. 1991. Plynlimon research: The first two decades.
Kirkby, M. J. (1978). *Hillslope hydrology,* Chichester, Wiley.

Klein, M. (1984). Anti clockwise hysteresis in suspended sediment concentration during individual storms: Holbeck catchment; yorkshire, england. *Catena,* **11,** 251 - 257.
Labadz, J. C., Burt, T. P. & Potter, A. W. R. (1991). Sediment yield and delivery in the blanket peat moorlands of the southern pennines. *Earth Surface Processes and Landforms,* **16,** 255-271.
Lake, R. G. & Hinch, S. G. (1999). Acute effects of suspended sediment angularity on juvenile coho salmon (oncorhynchus kisutch) *Canadian Journal of Fisheries and Aquatic Sciences,* **56,** 862 - 867.
Lane, L. J., Hernandez, M. & Nichols, M. (1997). Processes controlling sediment yield from watersheds as functions of spatial scale. *Environmental modelling,* **12,** 355 - 369.
Lane, S. N., Brookes, C. J., Kirkby, M. J. & Holden, J. (2004). A network-index-based version of topmodel for use with high-resolution digital topographic data. *Hydrological Processes,* **18,** 191-201.
Lane, S. N., Brookes, C. J., Louise Heathwaite, A. & Reaney, S. (2006). Surveillant science: Challenges for the management of rural environments emerging from the new generation diffuse pollution models. *Journal of Agricultural Economics,* **57,** 239-257.
Lane, S. N., Tayefi, V., Reid, S. C., Yu, D. & Hardy, R., J (2007). Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms,* **32,** 429 - 446.
Langlois, J. L., Johnson, D. W. & Mehuys, G. R. (2005). Suspended sediment dynamics associated with snowmelt runoff in a small mountain stream of lake tahoe (nevada). *Hydrological Processes,* **19,** 3569-3580.
Lawler, D. M., Petts, G. E., Foster, I. D. L. & Harper, S. (2006). Turbidity dynamics during spring storm events in an urban headwater river system: The upper tame, west midlands, uk. *Science of The Total Environment,* **360,** 109-126.
Leecaster, M. K., Schiff, K. & Tiefenthaler, L. L. (2002). Assessment of efficient sampling designs for urban stormwater monitoring. *Water Research,* **36,** 1556-1564.
Leeks, G. J. L. & Marks, S. D. (1997). Dynamics of river sediments in forested headwater streams: Plynlimon. *Hydrology and Earth System Sciences,* **1,** 483 - 497.
Leeks, G. J. L. & Roberts, G. (eds.) (1987). *The effects of forestry on upland streams - with special reference to water quality and sediment transport,* Grange-over-Sands: NERC/ITE.
Lees, J., Foster, I., Jones, D., Owens, P., Walling, D. & Leeks, G. (1997). Sediment yields in a changing environment: A historical reconstruction using reservoir bottom-sediments in three contrasting small catchments, north york moors, uk. *IAHS Publication***,** 169-179.
Lefrançois, J., Grimaldi, C., Gascuel-Odoux, C. & Gillet, N. (2007). Suspended sediment and discharge relationships to identify bank degradation as a main sediment source on small agricultural catchments. *Hydrological Processes,* **21,** 2923 - 2933.
Lewis, J. (1996). Turbidity-controlled suspended sediment sampling for runoff-event load estimation. *Water Resources Research,* **32,** 2299 - 2310.
Lewis, J. 2003. Turbidity-controlled sampling for suspended sediment load estimation. California: USDA Forest Service.
Lewis, J. 2007. Comparisons of turbidity data collected with different instruments. *Report on a cooperative agreement between the California Department of Forestry and Fire Protection and USDA Forest Service - Pacific Southwest Research Station (PSW Agreement # 06-CO-11272133-041).*
Lewis, J. & Eads, R. (Year). Turbidity threshold sampling for suspended sediment load estimation. *In:* Proceedings of the Seventh Federal Interagency Sedimentation Conference, 2001 Reno, NV. 110 - 117.

Lewis, J. & Eads, R. 2008. Implementation guide for turbidity threshold sampling: Principles, procedures, and analysis. Arcata, CA: USA: Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Li, R., Zhu, A.-X., Song, X. & Cui, M. (2010). Seasonal dynamics of runoff-sediment relationship and its controlling factors in black soil region of northeast china. *Journal of Resources and Ecology,* **1,** 345 - 352.

Lisle, T. E. & Lewis, J. (1992). Effects of sediment transport on survival of salmonid embryos in a natural stream: A simulation approach. *Canadian Journal of Fisheries and Aquatic Sciences,* **49,** 2337 - 2344

Littlewood, I. G. 1992. Estimating contaminant loads in rivers: A review. Wallingford: Institute of Hydrology.

Littlewood, I. G. & Marsh, T. J. (2005). Annual freshwater river mass loads from great britain, 1975-1994: Estimation algorithm, database and monitoring network issues. *Journal of Hydrology,* **304,** 221-237.

Longfield, S. A. & Macklin, M. G. (1999). The influence of recent environmental change on flooding and sediment fluxes in the yorkshire ouse basin. *Hydrological Processes,* **13,** 1051-1066.

Lu, H., Moran, C. J. & Sivipalan, M. (2005). A theoretical exploration of catchment-scale sediment delivery. *Water Resources Research,* **41**.

Ludwig, K. A. & Hanes, D. M. (1990). A laboratory evaluation of optical backscatterance suspended solids sensors exposed to sand-mud mixtures. *Marine Geology,* **94,** 173-179.

Luppi, L., Rinaldi, M., Teruggi, L. B., Darby, S. E. & Nardi, L. (2009). Monitoring and numerical modelling of riverbank erosion processes: A case study along the cecina river (central italy). *Earth Surface Processes and Landforms,* **34,** 530-546.

Macdonald, L. H. & Coe, D. (2007). Influence of headwater streams on downstream reaches in forested areas. *Forest Science,* **53,** 148-168.

Machordom, A., Araujo, R., Erpenbeck, D. & Ramos, M.-Á. (2003). Phylogeography and conservation genetics of endangered european margaritiferidae (bivalvia: Unionoidea). *Biological Journal of the Linnean Society,* **78,** 235-252.

Madej, M. A. (2005). The role of organic matter in sediment budgets of forested terrain. *In:* Horowitz, A. J. & Walling, D. E. (eds.) *Sediment budgets 2 (proceedings of symposium s1 held during the seventh iahs scientific assembly).* Wallingford, Oxfordshire: IAHS Publications.

Mano, V., Nemery, J., Belleudy, P. & Poirel, A. (2009). Assessment of suspended sediment transport in four alpine watersheds (france): Influence of the climatic regime. *Hydrological Processes,* **23,** 777-792.

Marttila, H. & Kløve, B. (2010). Dynamics of erosion and suspended sediment transport from drained peatland forestry. *Journal of Hydrology,* **388,** 414-425.

Mather, A. S. (1978). The alleged deterioration in hill grazings in the scottish highlands. *Biological Conservation,* **14,** 181-195.

Mcbean, E. A. & Al-Nassri, S. (1988). Uncertainty in suspended sediment transport curves. *Journal of Hydraulic Engineering,* **114,** 63-74.

Mccartney, B. L. (2005). *Ship channel design and operation,* Reston, Virginia, ASCE.

Mcdonald, D. M., Lamoureux, S. F. & Warburton, J. (2010). Assessment of a time-integrated fluvial suspended sediment sampler in a high arctic setting. *Geografiska Annaler. Series A, Physical Geography,* **92,** 225 - 235.

Mchugh, M. (2000). *Extent, causes and rates of upland soil erosion in england and wales.* PhD, Cranfield University.

Mchugh, M. (2007). Short-term changes in upland soil erosion in england and wales: 1999 to 2002. *Geomorphology,* **86,** 204-213.

Mchugh, M., Harrod, T. & Morgan, R. (2002). The extent of soil erosion in upland england and wales. *Earth Surface Processes and Landforms,* **27,** 99-107.

Meade, R. H. (1996). River sediment inputs to major deltas. *In:* Milliman, J. D. & Haq, B. U. (eds.) *Sea-level rise and coastal subsidence.* Boston, MA: Kluwer Academic Publishing.

Meade, R. H. & Parker, R. S. 1985. Sediment in rivers of the united states. *National Water Summary.*

Meade, R. H., Yuzyk, T. R. & Day, T. J. (1990). Movement and storage of sediment in the rivers of the united states and canada. *In:* Wolman, M. G. & Riggs, H. C. (eds.) *Surface water hydrology: The geology of north america.* Boulder, Colorado: Geological Society of America.

Meybeck, M., Laroche, L., Dürr, H. H. & Syvitski, J. P. M. (2003). Global variability of daily total suspended solids and their fluxes in rivers. *Global and Planetary Change,* **39,** 65-93.

Meyer, J. L., Strayer, D. L., Wallance, J. B., Eggert, S. L., Helfman, G. S. & Leonard, N. E. (2007). The contribution of headwater streams to biodiversity in river networks. *Journal of the American Water Resources Association,* **43,** 86 - 103.

Milhous, R. T. (1990). Discussion of ``uncertainty in suspended sediment transport curves'' by edward a. Mcbean and sabah al-nassri (january, 1988, vol. 114, no. 1). *Journal of Hydraulic Engineering,* **116,** 730-732.

Milledge, D., Lane, S. N., Reaney, S. M. & Heathwaite, A. L. 2011. Can a static metric for hydrologic connectivity improve predictions of instream water quantity and quality? *EGU.* Vienna.

Mills, C. F., Bathurst, J. C. & Quinn, P. (Year). A study of spatial scaling in suspended sediment yield along a rural river system – the river eden, cumbria, uk. *In:* Sediment Dynamics in Changing Environments (Proceedings of a symposium held in Christchurch, New Zealand, December 2008), 2008. IAHS Publication, 217 - 224.

Minella, J. P. G., Merten, G. H., Reichert, J. M. & Clarke, R. T. (2007). Estimating suspended sediment concentrations from turbidity measurements and the calibration problem. *Hydrological Processes*.

Minella, J. P. G., Merten, G. H., Walling, D. E. & Reichert, J. M. (2009). Changing sediment yield as an indicator of improved soil management practices in southern brazil. *Catena,* **79,** 228-236.

Minella, J. P. G., Walling, D. E. & Merten, G. H. (2008). Combining sediment source tracing techniques with traditional monitoring to assess the impact of improved land management on catchment sediment yields. *Journal of Hydrology,* **348,** 546-563.

Minshall, G. W., Petersen, R. C., Cummins, K. W., Bott, T. L., Sedell, J. R., Cushing, C. E. & Vannote, R. L. (1983). Interbiome comparison of stream ecosystem dynamics. *Ecological Monographs,* **53,** 1 - 25.

Moore, R. J. & Newson, M. D. (1986). Production, storage and output of coarse upland sediments: Natural and artificial influences as revealed by research catchment studies. *Journal of the Geological Society,* **143,** 921-926.

Morehead, M. D., Syvitski, J. P., Hutton, E. W. H. & Peckham, S. D. (2003). Modeling the temporal variability in the flux of sediment from ungauged river basins. *Global and Planetary Change,* **39,** 95-110.

Morgan, R. P. C. (1995). *Soil erosion and conservation,* London, Longman.

Morris, G. L. & Fan, J. (1998). *Reservoir sedimentation handbook: Design and management of dams, reservoirs, and watersheds for sustainable use,* New York, USA, McGraw-Hill Professional.

Moss, B. (2008). The water framework directive: Total environment or political compromise? *Science of The Total Environment,* **400,** 32 - 42.
Naden, P. (2010). The fine-sediment cascade. *In:* Burt, T. P. & Allison, R. (eds.) *Sediment cascades: An integrated approach.* Chichester, UK: Wiley & Sons.
Naiman, R. J. (1982). Characteristics of sediment and organic carbon export from pristine boreal forest watersheds. *Canadian Journal of Fisheries and Aquatic Sciences,* **39,** 1699 - 1718.
Naiman, R. J., Melillo, J. M., Lock, M. A., Ford, T. E. & Reice, S. R. (1987). Longitudinal patterns of ecosystem processes and community structure in a subarctic river continuum. *Ecology,* **68,** 1139 - 1156.
Nash, J. E. & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models. Part i - a discussion of principles. *Journal of Hydrology,* **10,** 282 - 290.
Natural England 2008. Investigations into the use of critical sediment yields for assessing and managing fine sediment inputs into freshwater ecosystems.
Navratil, O., Esteves, M., Legout, C., Gratiot, N., Nemery, J., Willmore, S. & Grangeon, T. (2011). Global uncertainty analysis of suspended sediment monitoring using turbidimeter in a small mountainous river catchment. *Journal of Hydrology,* **398,** 246-259.
Nelson, M. E. & Benedict, P. C. 1951. Measurement and analysis of suspended sediment stream loads in streams. ASCE.
Newburn, L. H. (1988). Modern sampling equipment: Design and application. *In:* Keith, L. H. (ed.) *Principles of environmental sampling.* Salem, MA: USA: American Chemical Society.
Newson, M. & Sear, D. (2007). The role of geomorphology in monitoring and managing river sediment systems. *Water and Environment Journal,* **11,** 264-270.
Newson, M. D. & Sear, D. (1998). The role of geomorphology in monitoring and managing river sediment systems. *Water and Environment Journal,* **12,** 18-24.
Newson, M. D., Sear, D. & Orr, H. G. 2008. Evaluating fine sediment problems in freshwater ecosystems: A fluvial geomorphological perspective. *In:* Walling, D. E. & Webb, B. W. (eds.) *Investigations into the use of critical sediment yields for assessing and managing fine sediment inputs into freshwater ecosystems.* Sheffield: Natural England.
Nieuwenhuyse, E. E. & Laperriere, J. D. (1986). Effects of placer gold mining on primary production in subarctic streams of alaska¹. *Journal of the American Water Resources Association,* **22,** 91-99.
Nordin, C. F. 1963. A preliminary study of sediment transport parameters, rio, puerco, near bernado, new mexico. U.S. Geological Survey Professional Paper.
Nordin, C. F. (1990). Discussion of ``uncertainty in suspended sediment transport curves'' by edward a. Mcbean and sabah al-nassri (january, 1988, vol. 114, no. 1). *Journal of Hydraulic Engineering,* **116,** 145-148.
North York Moors National Park Authority 2001. River esk regeneration programme, july 1997 - october 2001.
Oeurng, C., Sauvage, S. & Sánchez-Pérez, J.-M. (2010). Dynamics of suspended sediment transport and yield in a large agricultural catchment, southwest france. *Earth Surface Processes and Landforms,* **35,** 1289-1301.
Old, G. H., Leeks, G. J. L., Packman, J. C., Smith, B. P. G., Lewis, S., Hewitt, E. J., Holmes, M. & Young, A. (2003). The impact of a convectional summer rainfall event on river flow and fine sediment transport in a highly urbanised catchment: Bradford, west yorkshire. *The Science of the Total Environment,* **314-316,** 495-512.
Onda, Y., Mizugaki, S., Fukuyama, T., Koga, S., Asai, H. & Hiramatsu, S. 2007. Estimation of suspended sediment sources using cs-137 and pb210ex in unmanaged japanese

cypress plantation watersheds of southern japan. *American Geophysical Union, Fall Meeting 2007.*
Ongley, E. D. (Year). Influence of season, source and distance on physical and chemical properties of suspended sediment. *In:* Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield. , 1982 Proceedings of the Exeter Symposium, July 1982. IAHS Publication.
Ongley, E. D. (1992). *Environmental quality: Changing times for sediment programs,* Wallingford, Int Assoc Hydrological Sciences.
Ongley, E. D., Krishnappan, B. G., Droppo, G., Rao, S. S. & Maguire, R. J. (1992). Cohesive sediment transport: Emerging issues for toxic chemical management. *Hydrobiologia,* **235-236,** 177-187.
Orwin, J. F., Lamoureux, S. F., Warburton, J. & Beylick, A. (2010). A framework for characterising fluvial sediment fluxes from source to sink in cold environments. *Geografiska Annaler. Series A, Physical Geography,* **92,** 155 - 176.
Osterkamp, W. R. & Toy, T. J. (1997). Geomorphic considerations for erosion prediction. *Environmental Geology,* **29**.
Owen, G. J., Perks, M. T., Benskin, C. M. H., Wilkinson, M. E., Jonczyk, J. & Quinn, P. F. (2012). Monitoring agricultural diffuse pollution through a dense monitoring network in the river eden demonstration test catchment, cumbria, uk. *Area,* **44,** 443-453.
Owens, P. (2005). Conceptual models and budgets for sediment management at the river basin scale. *Journal of Soils and Sediments,* **5,** 201-212.
Owens, P. N. (2008). Sediment behaviour, functions and management in river basins. *In:* Owens, P. N. (ed.) *Sustainable management of sediment resources.* Elsevier.
Owens, P. N. & Collins, A. J. (2005). Soil erosion and sediment redistribution in river catchments: Sumary, outlook and future requirements. *In:* Owens, P. N. & Collins, A. J. (eds.) *Soil erosion and sediment redistribution in river catchments.* Wallingford, UK: CAB International.
Parsons, A. J., Wainwright, J., Brazier, R. E. & Powell, D. M. (2006). Is sediment delivery a fallacy? *Earth Surface Processes and Landforms,* **31,** 1325 - 1328.
Parsons, A. J., Wainwright, J., Powell, D. M., Kaduk, J. & Brazier, R. E. (2004). A conceptual model for determining soil erosion by water. *Earth Surface Processes and Landforms,* **29,** 1293 - 1302.
Paustian, S. J. & Beschta, R. L. (1979). The suspended sediment regime of an oregon coast range stream. *JAWRA Journal of the American Water Resources Association,* **15,** 144-154.
Pavanelli, D. & Bigi, A. (2005). A new indirect method to estimate suspended sediment concentration in a river monitoring programme. *Biosystems Engineering,* **92,** 513 - 520.
Pavelich, M. P. (Year). Turbidity studies at the national water quality laboratory. *In:* Turbidity and other surrogates workshop, April 30 - May 2 2002 Reno, NV.
Phillips, J. M., Russell, M. A. & Walling, D. E. (2000). Time-integrated sampling of fluvial suspended sediment: A simple methodology for small catchments. *Hydrological Processes,* **14,** 2589 - 2602.
Phillips, J. M. & Walling, D. E. (1999). The particle size characteristics of fine-grained channel deposits in the river exe basin, devon, uk. *Hydrological Processes,* **13,** 1-19.
Phillips, J. M., Webb, B. W., Walling, D. E. & Leeks, G. J. L. (1999). Estimating the suspended sediment loads of rivers in the lois study area using infrequent samples. *Hydrological Processes,* **13,** 1065 - 1050.

Pimental, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., Mcnair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. & Blair, R. (1995). Environmental and economic costs of soil erosion and conservational benefits. *Science,* **267,** 1117 - 1123.

Poesen, J. & Savat, J. (1981). Detachment and transportation of loose sediments by raindrop splash: Part ii detachability and transport ability measurements. *Catena,* **8,** 19-41.

Poesen, J., Vandaele, K. & Van Wesemael, B. (Year). Contribution of gully erosion to sediment production on cultivated lands and rangelands. *In:* Walling, D. E. & Webb, B. W., eds. Erosion and Sediment Yield: Global and Regional Perspectives, 1996. IAHS Symposium, 251 - 266.

Porterfield, G. 1977. Computation of fluvial-sediment discharge. *Techniques of Water-Resources investigations of the United States Geological Survey.* USGS.

Pratt, T. & Parchure, T. (Year). Obs calibration and field measurements. *In:* Federal Interagency workshop on turbidity and other sediment surrogates, 30 April - May 2 2002 Reno, NV.

Preston, S. D., Bierman, V. J., Jr. & Silliman, S. E. (1989). An evaluation of methods for the estimation of tributary mass loads. *Water Resour. Res.,* **25,** 1379-1389.

Pruitt, B. A. (Year). Use of turbidity by state agencies. *In:* Turbidity and Other Sediment Surrogates Workshop, April 30 - May 2, 2003 Reno, NV.

Quilbé, R., Rousseau, A. N., Duchemin, M., Poulin, A., Gangbazo, G. & Villeneuve, J.-P. (2006). Selecting a calculation method to estimate sediment and nutrient loads in streams: Application to the beaurivage river (québec, canada). *Journal of Hydrology,* **326,** 295-310.

Ramesh, R. & Subramanian, V. (1988). Temporal, spatial and size variation in the sediment transport in the krishna river basin, india. *Journal of Hydrology,* **98,** 53-65.

Rannie, W. F. (1987). An approach to the prediction of suspended sediment rating curves. *In:* Davidson-Arnott, R. & Nickling, W. (eds.) *Research in fluvial systems.* Norwich: Geoabstracts.

Reaney, S. M., Lane, S. N., Heathwaite, A. L. & Dugdale, L. J. (2011). Risk-based modelling of diffuse land use impacts from rural landscapes upon salmonid fry abundance. *Ecological Modelling,* **222,** 1016-1029.

Renschler, C. S. & Harbor, J. (2002). Soil erosion assessment tools from point to regional scales—the role of geomorphologists in land management research and implementation. *Geomorphology,* **47,** 189-209.

Reynolds, B. (1986). A comparison of element outputs in solution, suspended sediments and bedload for a small upland catchment. *Earth Surface Processes and Landforms,* **11,** 217-221.

Richardson, J. S., Naiman, R. J., Swanson, F. J. & Hibbs, D. E. (2005). Riparian communities associated with pacific northwest headwater streams: Assemblages, processes, and uniqueness. *JAWRA Journal of the American Water Resources Association,* **41,** 935 - 947.

Rinaldi, M., Casagli, N., Dapporto, S. & Gargini, A. (2004). Monitoring and modelling of pore water pressure changes and riverbank stability during flow events. *Earth Surface Processes and Landforms,* **29,** 237-254.

Rinaldi, M. & Darby, S. E. (2008). Modelling river-bank-erosion processes and mass failure mechanisms: Progress towards fully coupled simulations. *In:* Habersack, H., Rinaldi, M. & Piégay, H. (eds.) *Gravel bed rivers vi: From process understanding to river restoration.* Amsterdam, Holland: Elsevier.

Robinson, A. R. (1973). Sediment, our greatest pollutant. *In:* Tank, R. (ed.) *Focus on environmental geology; geologic hazards and hostile environments; erosion sedimentation and floods.* London: Oxford University Press.

Robinson, M. 1990. Impact of improved land drainage on river flows. Institute of Hydrology.
Robinson, M. & Blyth, K. (1982a). The effect of forestry drainage operation on upland sediment yields - a case-study. *Earth Surface Processes and Landforms,* **7,** 85-90.
Robinson, M. & Blyth, K. (1982b). The effect of forestry drainage operations on upland sediment yields: A case study. *Earth Surface Processes and Landforms,* **7,** 85-90.
Rodríguez-Blanco, M. L., Taboada-Castro, M. M. & Taboada-Castro, M. T. (2010). Linking the field to the stream: Soil erosion and sediment yield in a rural catchment, nw spain. *Catena,* **In Press, Corrected Proof**.
Rosenberg, D. M. & Wiens, A. P. (1978). Effects of sediment addition on macrobenthic invertebrates in a northern canadian river. *Water Research,* **12,** 753-763.
Rovira, A. & Batalla, R. J. (2006). Temporal distribution of suspended sediment transport in a mediterranean basin: The lower todera (ne spain). *Geomorphology,* **79,** 58-71.
Russell, M. A., Walling, D. E. & Hodgkinson, R. A. (2000). *Appraisal of a simple sampling device for collecting time-integrated fluvial suspended sediment samples,* Wallingford, International Association of Hydrological Sciences.
Russell, M. A., Walling, D. E. & Hodgkinson, R. A. (2001). Suspended sediment sources in two small lowland agricultural catchments in the uk. *Journal of Hydrology,* **252,** 1 - 24.
Sable, K. A. & Wohl, E. (2006). The relationship of lithology and watershed characteristics to fine sediment deposition in streams of the oregon coast range. *Environmental Management,* **37,** 659-670.
Sadar, M. 1998. Turbidity science. *Technical Information Series - Booklet No. 11, .*
Sadar, M. (Year). Turbidity instrumentation - an overview of today's available technology. *In:* Turbidity and other sediment surrogates workshop, April 30 - May 2 2002 Reno, NV.
Sadar, M. 2004. An introduction to laser nephelometry: An alternative to conventional particulate analysis methods Hach.
Sadeghi, S. H. R., Mizuyama, T., Miyata, A., Gomi, T., Kosugi, K., Fukushima, T., Mizugaki, S. & Onda, Y. (2008). Development, evaluation and interpretation of sediment rating curves for a japanese small mountainous reforested watershed. *Geoderma,* **144,** 198 - 211.
Salant, N. L., Hassan, M. A. & Alonso, C. V. (2008). Suspended sediment dynamics at high and low storm flows in two small watersheds. **22,** 1573-1587.
Sayer, A. M., Walsh, R. P. D. & Bidin, K. (2006). Pipeflow suspended sediment dynamics and their contribution to stream sediment budgets in small rainforest catchments, sabah, malaysia. *Forest Ecology and Management,* **224,** 119-130.
Schindl, G., Studnicka, M., Eckelhart, A. & Summer, W. (2005). Hydrological and instrumentation apsects of monitoring and analysing suspended sediment transport crossing international borders. *In:* Walling, D. E. & Horowitz, A. J. (eds.) *Sediment budgets i (proceedings of symposium si held during the seventh iahs scientific assembly at foz de iguacu, brazil)*
Schoellhamer, D. H. & Wright, S. A. (Year). Continuous monitoring of suspended sediment in rivers by use of optical backscatterance sensors. Erosion and sediment transport measurements: Technological and methodological advances. *In:* Proceedings of a Workshop, 2002 Oslo. International Association of Hydrological Sciences (IAHS), 28 - 36.
Schumm, S. A. (1977). *The fluvial system,* New York, USA, Wiley.
Scrudato, R., Yogis, G. & Hocutt, G. (1988). An in-situ integrated suspended sediment stream sampler (is^3). *Environmental Geology,* **12,** 177-179.
Sear, D. & Archer, D. R. (1998). The effects of gravel extraction on the stability of gravel-bed rivers: A case study from the wooler water, northumberland, uk. *In:* Klingeman, P.,

Beschta, R. L., Komar, B. D. & Milhous, R. T. (eds.) *Gravel bed rivers in the environment.* Colorado, USA: Water Research Counci.
Sear, D. A., Newson, M. D. & Brookes, A. (1995). Sediment-related river maintenance: The role of fluvial geomorphology. *Earth Surface Processes and Landforms,* **20,** 629-647.
Sednet 2009. Integration of sediment in river basin management. *Report on the 2nd SedNet Round Table Discussion.*
Seeger, M., Errea, M.-P., Beguería, S., Arnáez, J., Martí, C. & García-Ruiz, J. M. (2004). Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the spanish pyrenees. *Journal of Hydrology,* **288,** 299 - 311.
Shalash, S. (1982). Effects of sedimentation on the storage capacity of the high aswan dam reservoir. *Hydrobiologia,* **91-92,** 623-639.
Sheldon, L. R. 1994. Field guide for collecting and processing stream-water samples for the national water-quality assessment program.
Simmons, I. G. (2003). *The moorlands of england and wales: An environmental history 8000 bc - ad 2000,* Edinburgh, Edinburgh University Press.
Simon, A., Dickerson, W. & Heins, A. (2004). Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the united states: Transport conditions at the bankfull and effective discharge? *Geomorphology,* **58,** 243-262.
Singer, M. B. & Dunne, T. (2001). Identifying eroding and depositional reaches of valley by analysis of suspended sediment transport in the sacramento river, california. *Water Resour. Res.,* **37,** 3371-3381.
Skarbøvik, E., Stålnacke, P., Bogen, J. & Bønsnes, T. E. (2012). Impact of sampling frequency on mean concentrations and estimated loads of suspended sediment in a norwegian river: Implications for water management. *Science of The Total Environment,* **433,** 462-471.
Skinner, A., Young, M. & Hastie, L. 2003. Ecology of the freshwater pearl mussel. *Conserving Natura 2000 Rivers.* Peterborough: English Nature.
Slattery, M. C. & Burt, T. P. (1997). Particle size characteristics of suspended sediment in hillslope runoff and stream flow. *Earth Surface Processes and Landforms,* **22,** 705-719.
Smith, B. P. G., Naden, P. S., Leeks, G. J. L. & Wass, P. D. (2003). The influence of storm events on fine sediment transport, erosion and deposition within a reach of the river swale, yorkshire, uk. *Science of The Total Environment,* **314–316,** 451-474.
Smith, H. G. & Dragovich, D. (2008). Improving precision in sediment source and erosion process distinction in an upland catchment, south-eastern australia. *Catena,* **72,** 191 - 203.
Smith, H. G. & Dragovich, D. (2009). Interpreting sediment delivery processes using suspended sediment-discharge hysteresis patterns from nested upland catchments, south-eastern australia. *Hydrological Processes,* **23,** 2415-2426.
Soutar, R. G. (1989). Afforestation and sediment yields in british fresh waters. *Soil Use and Management,* **5,** 82-86.
Spott, D. & Guhr, H. (Year). The dynamics of suspended solids in the tidally unelected river elbe as a function of flow and shipping. *In:* Preprints of the International Symposium on particulate matter in rivers and estuaries, 1994 Reinbek. 267 - 273.
Spratt, D. A. & Harrison, B. J. D. (1989). *The north york moors: Landscape heritage,* London, David & Charles.
Stone, P. M. & Saunderson, H. C. (Year). Regional patterns of sediment yield in the laurentian great lakes basin. *In:* Erosion and sediment yield: Global and regional perspectives, 1996 Proceedings of the Exeter Symposium. IAHS, 125 - 131.

Stone, P. M. & Walling, D. E. (1997). Particle size selectivity considerations in suspended sediment budget investigations. *Water, Air, & Soil Pollution,* **99,** 63-70.

Strauss, P., Leone, A., Ripa, M. N., Turpin, N., Lescot, J. M. & Laplana, R. (2007). Using critical source areas for targeting cost-effective best management practices to mitigate phosphorus and sediment transfer at the watershed scale. *Soil Use and Management,* **23,** 144-153.

Strobl, R. O. & Robillard, P. D. (2008). Network design for water quality monitoring of surface freshwaters: A review. *Journal of Environmental Management,* **87,** 639-648.

Stutter, M. I., Langan, S. J. & Cooper, R. J. (2008). Spatial and temporal dynamics of stream water particulate and dissolved n, p and c forms along a catchment transect, ne scotland. *Journal of Hydrology,* **350,** 187-202.

Sutherland, T. F., Lane, P. M., Amos, C. L. & Downing, J. (2000). The calibration of optical backscatter sensors for suspended sediment of varying darkness levels. *Marine Geology,* **162,** 587-597.

Syvitski, J. P. M. & Kettner, A. J. (Year). Scaling sediment flux across landscapes. *In:* Proceedings of the 2008 Symposium of the International Commission on Continental Erosion, Christchurch, New Zealand, 1-5 December 2008, 2008.

Syvitski, J. P. M., Vorosmarty, C. J., Kettner, A. J. & Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science,* **308,** 376 - 380.

Tazioli, G. S. (1980). The measurement of suspended sediment transport in natural streams using automatic radioisotope gauges. *Journal of Hydrology,* **47,** 173-185.

Teixeira, E. C. & Caliari, P. C. (Year). Estimation of the concentration of suspended solids in rivers from turbidity measurement: Error assessment. *In:* Walling, D. E. & Horowitz, A. J., eds. Sediment Budgets 1, 2005 Proceedings of symposium S1 held during the Seventh IASH Scientific Assembly at Foz do Iguaçu, Brazil. IAHS Publication, 151 - 160.

Tessier, C., Le Hir, P., Lurton, X. & Castaing, P. (2008). Estimation of suspended sediment concentration from backscatter intensity of acoustic doppler current profiler. *Comptes Rendus Geosciences,* **340,** 57-67.

Thomas, R. B. (1985). Estimating total suspended sediment yield with probability sampling. *Water Resources Research,* **21,** 1381 - 1388.

Thomas, R. B. (1988). Monitoring baseline suspended sediment in forested basins: The effects of sampling on suspended sediment rating curves. *Hydrological Sciences Journal,* **33,** 499 - 514.

Thomas, R. B. & Lewis, J. (1993). A comparison of selection at list time and time-stratified sampling for estimating suspended sediment loads. *Water Resour. Res.,* **29,** 1247-1256.

Thomas, R. B. & Lewis, J. (1995). An evaluation of flow-stratified sampling for estimating suspended sediment loads. *Journal of Hydrology,* **170,** 27-45.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R. & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature,* **418,** 671-677.

Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F. & Ward, J. V. (1999). Hydrological connectivity, and the exchange of organic matter and nutrients in a dynamic river–floodplain system (danube, austria). *Freshwater Biology,* **41,** 521-535.

Topping, D. J., Wright, S. A., Melis, T. S. & Rubin, D. M. (Year). High-resolution measurements of suspended-sediment concentration and grain size in the colorado river in grand canyon using a multi-frequency acoustic system *In:* Proceedings of the Tenth International Symposium on River Sedimentation 1 - 4 August 2007 Moscow, Russia. 330 - 339.

Trauth, M. H. (2010). Matlab recipes for earth sciences. London: Springer.

Trimble, S. W. (1983). A sediment budget for coon creek basin in the driftless area, wisconsin. *Science,* **283,** 454 - 474.
Turnpenny, A. W. H. & Williams, R. (1980). Effects of sedimentation on the gravels of an industrial river system. *Journal of Fish Biology,* **17,** 681 - 693.
United Nations Environment Programme & World Health Organization 1996. Water quality monitoring - a practical guide to the design and implementation of freshwater quality studies and monitoring programmes. *In:* Bartram, J. & Ballance, R. (eds.). UNEP/WHO.
United States Environmental Protection Agency. (1993). Method 180.1: Determination of turbidity by nephelometry. Available: http://www.epa.gov/waterscience/methods/method/files/180_1.pdf.
Vaithiyanathan, P., Ramanathan, A. & Subramanian, V. (1992). Sediment transport in the cauvery river basin: Sediment characteristics and controlling factors. *Journal of Hydrology,* **139,** 197-210.
Vandekerckhove, L., Poesen, J., Oostwoud Wijdenes, D., Nachtergaele, J., Kosmas, C., Roxo, M. J. & De Figueiredo, T. (2000). Thresholds for gully initiation and sedimentation in mediterranean europe. *Earth Surface Processes and Landforms,* **25,** 1201 - 1220.
Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences,* **37,** 130 - 137.
Vanoni, V. A. 2006. Sedimentation engineering: Manuals and reports on engineering practice no. 54. *In:* Vanoni, V. A. (ed.). Reston, VA: American Society of Civil Engineers Publications.
Vongvixay, A., Grimaldi, C., Gascuel-Odoux, C., Laguionie, P., Faucheux, M., Gilliet, N. & Mayet, M. (Year). Analysis of suspended sediment concentration and discharge relations to identify particle origins in small agricultural watersheds. *In:* Sediment Dynamics for a Changing Future: Proceedings of the ICCE symposium held at Warsaw University of Life Sciences - SGGW, Poland, 14–18 June 2010, 2010. IAHS Publications.
Wainwright, J., Turnbull, L., Ibrahim, T. G., Lexartza-Artza, I., Thornton, S. F. & Brazier, R. E. (2011). Linking environmental régimes, space and time: Interpretations of structural and functional connectivity. *Geomorphology,* **126,** 387-404.
Walling, D. (2006). Tracing versus monitoring: New challenges and opportunities in erosion and sediment delivery research. *Soil erosion and sediment redistribution in river catchments***,** 13-27.
Walling, D. E. (1974). Suspended sediment and solute yields from a small catchment prior to urbanization. *In:* Gregory, K. J. & Walling, D. E. (eds.) *Inst. Brit. Geogr. Spec. Publ: Fluvial processes in instrumented watersheds*
Walling, D. E. (1977). Assessing the accuracy of suspended sediment ratnig curves for a small basin. *Water Resources Research,* **13,** 531 - 538.
Walling, D. E. (1978). Reliability considerations in the evaluation and analysis of river loads. *Z. Geomorphol., Suppl. Bd.,* **29,** 29 - 42.
Walling, D. E. (1983). The sediment delivery problem. *Journal of Hydrology,* **65,** 209 - 237.
Walling, D. E. (Year). Sediment yields of african rivers. *In:* Challenges in African Hydrology and Water Resources: Proceedings of the Harare Symposium July 1984. IAHS Publication, 1984.
Walling, D. E. (1999). Linking land use, erosion and sediment yields in river basins. *Hydrobiologia,* **410,** 223 - 240.
Walling, D. E. (2005). Tracing suspended sediment sources in catchments and river systems. *Science of The Total Environment,* **344,** 159-184.

Walling, D. E., Collins, A. J. & Mcmellin, G. 2001. Provenance of insterstitial sediment retrieved from salmonid spawning gravels in england and wales. Bristol.
Walling, D. E. & Collins, A. L. (2008). The catchment sediment budget as a management tool. *Environmental Science & Policy,* **11,** 136-143.
Walling, D. E., Collins, A. L. & Stroud, R. W. (2008a). Tracing suspended sediment and particulate phosphorus sources in catchments. *Journal of Hydrology,* **350,** 274-289.
Walling, D. E., Collins, A. L. & Stroud, R. W. (2008b). Tracing suspended sediment and particulate phosphorus sources in catchments. *Journal of Hydrology,* **350,** 274 - 289.
Walling, D. E. & Moorehead, P. W. (1987). Spatial and temporal variation of the particle-size characteristics of fluvial suspended sediment. *Geografiska Annaler. Series A, Physical Geography,* **69,** 47-59.
Walling, D. E. & Moorehead, P. W. (1989). The particle size characteristics of fluvial suspended sediment: An overview. *Hydrobiologia,* **176-177,** 125-149.
Walling, D. E., Owens, P. N. & Leeks, G. J. L. (1999). Rates of contemporary overbank sedimentation and sediment storage on the floodplains of the main channel systems of the yorkshire ouse and river tweed, uk. *Hydrological Processes,* **13,** 993-1009.
Walling, D. E., Owens, P. N., Waterfall, B. D., Leeks, G. J. L. & Wass, P. D. (2000). The particle size characteristics of fluvial suspended sediment in the humber and tweed catchments, uk. *The Science of The Total Environment,* **251-252,** 205-222.
Walling, D. E. & Teed, A. (1971). A simple pumping sampler for research into suspended sediment transport in small catchments. *Journal of Hydrology,* **13,** 325-337.
Walling, D. E. & Webb, B. W. (1981). Water quality. *In:* Lewin, J. (ed.) *British rivers.* London: George Allen & Unwin.
Walling, D. E. & Webb, B. W. (1987). Suspended load in gravel bed rivers: Uk experience. *In:* Thorne, C. R., Bathurst, J. C. & Hey, R. D. (eds.) *Sediment transport in gravel bed rivers.* Chichester: Wiley & Sons.
Walling, D. E. & Webb, B. W. (Year). The reliability of suspended sediment load data. *In:* Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981), 1988. IAHS, 177 - 194.
Walling, D. E. & Webb, B. W. (1996). Erosion and sediment yield: A global overview. *In:* Walling, D. E. & Webb, B. W. (eds.) *Erosion and sediment yield: Global and regional perspectives, iahs publication no. 236.* Wallingford: IAHS Press.
Walling, D. E., Webb, B. W. & Russell, M. A. (1997). Sediment-associated nutrient transport in uk rivers. *In:* Webb, B. W. (ed.) *Freshwater contamination: Proceedings of an international symposium (symposium s4) held during the fifth scientific assembly of the international association of hydrological sciences (iahs) at rabat, morocco, from 23 april to 3 may 1997, iahs publication no. 243.* Wallingford: IAHS Press.
Walling, D. E., Webb, B. W. & Woodward, J. C. (Year). Some sampling considerations in the design of effective stratergies for monitoring sediment-associated transport. *In:* Bogen, J., Walling, D. E. & Day, T. J., eds. Erosion and sediment transport monitoring programmes in river basins (Proceedings of the Oslo symposium, August 1992), 1992. IAHS, 279 - 289.
Warburton, J. (2007). Glaisdale beck diversion review. *Private Consultancy Report,* **Durham University**.
Warrick, J. A. & Rubin, D. M. (2007). Suspended-sediment rating curve response to urbanization and wildfire, santa ana river, california. *J. Geophys. Res.,* **112,** F02018.
Wass, P. D. & Leeks, G. J. L. (1999). Suspended sediment fluxes in the humber catchment, uk. *Hydrological Processes,* **13,** 935 - 953.

Water Framework Directive 2000. Directive 2000/60/ec of the european parliament and of the council of 23 october 2000. Official journal of the european communities (22.12.2000).

Webb, B. W. & Walling, D. E. (1982). The magnitude and frequency characteristics of fluvial transport in a devon drainage basin and some geomorphological implications. *Catena,* **9,** 9 - 23.

Webster, J. R., Benfield, E. F., Ehrman, T. P., Schaeffer, M. A., Tank, J. L., Hutchens, J. J. & D'angelo, D. J. (1999). What happens to allochthonous material that falls into streams? A synthesis of new and published information from coweeta. *Freshwater Biology,* **41,** 687-705.

Wetzel, H., Corners, H. & Manny, B. A. (1977). Seasonal changes in particulate and dissolved organic carbon and nitrogen in a hardwater stream. *Archiv für Hydrobiologie,* **80,** 20 - 39.

Wilkinson, S. N. 2008. Testing the capability of a sediment budget model for targeting remediation measures to reduce suspended-sediment yield. *Proceedings of the 2008 Symposium of the International Commission on Continental Erosion, Christchurch, New Zealand, 1-5 December 2008.* International Association of Hydrological Sciences.

Williams, G. P. (1989). Sediment concentration versus water discharge during single hydrologic events in rivers. *Journal of Hydrology,* **111,** 89 - 106.

Wolman, M. G. & Miller, W. P. (1960). Magnitude and frequency of forces in geomorphic processes. *Journal of Geology,* **68,** 54 - 74.

Wood, P. A. (1977). Controls of variation in suspended sediment concentration in the river rother, west sussex, england. *Sedimentology,* **24,** 437 - 445.

Wood, P. J. & Armitage, P. D. (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management,* **21,** 203-217.

Woodward, J. & Foster, I. A. N. (1997). Erosion and suspended sediment transfer in river catchments: Environmental controls, processes and problems. *Geography,* **82,** 353-376.

Woodward, J. C. & Walling, D. E. (2007). Composite suspended sediment particles in river systems: Their incidence, dynamics and physical characteristics. *Hydrological Processes,* **21,** 3601 - 3614.

Wren, D. G. (Year). Surrogate techniques for suspended-sediment measurement. *In:* Turbidity and other sediment surrogates workshop, April 30 - May 2 2002 Reno, NV.

Wren, D. G., Barkdoll, B. D., Kuhnle, R. A. & Derrow, R. W. (2000). Field techniques for suspended-sediment measurement. *Journal of Hydraulic Engineering,* **126,** 97-104.

Young, R. A. (1980). Characteristics of eroded sediment. *Transactions of the ASAE,* **23,** 1139 - 1142.

Zabaleta, A. & Antigedad, I. (2012). Temporal variations of suspended sediment transport in three small catchments of the basque country. *Zeitschrift für Geomorphologie, Supplementary Issues,* **56,** 81-98.

Ziegler, A. C. 2002. Issues related to the use of turbidity measurements as a surrogate for suspended sediment. *Turbidity and Other Sediment Surrogates Workshop.* Reno, NV.